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DEGREE PROGRAMME IN ELECTRONICS AND COMMUNICATIONS ENGINEERING

MASTER’S THESIS

INTERFERENCE ANALYSIS OF HIGH FREQUENCY POWER LINE COMMUNICATIONS

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ABSTRACT

In power line communications, the existing in-house or in-office power distribution network can be used as a communications channel. Current broadband power line communication systems in the market deploy frequency range up to 86 MHz with transmission speeds up to 1 Gb/s. To increase the capacity even further, an extension of the frequency range above 100 MHz has been proposed in the published literature. This thesis presents an empirical study of radiated interference of high frequency broadband power line communications. Utilization of high frequencies for power line communications will cause unwanted radio interference which needs to be treated with caution. The preliminary results obtained in this work show how the components and structures of a power grid segment will contribute to the overall interference radiation when frequencies above 100 MHz are used for power line communication. The results indicate that the peak levels of radiated interference from a typical cabling in in-house or in-office power line networks reach their maximum on frequencies near 300 MHz and remain on a relatively same level on above. The peak levels are approximately 13 dB above the EN 55022 limit in the 230 MHz – 1000 MHz frequency range with an injected power spectral density of -80 dBm/Hz. The results will provide valuable information when designing and making more comprehensive measurement campaigns for deciding on the national transmission levels for power line communications in UHF and higher frequencies.

Key words: electromagnetic compatibility, power line cable, simulation, measurements.

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TIIVISTELMÄ

Sähköverkkotiedonsiirrossa hyödynnetään olemassa olevaa sähköverkkoa tiedonsiirtokanavana. Tällä hetkellä käytössä olevat sähköverkkotiedonsiirron standardit käyttävät taajuuksia 86 MHz:iin asti. Saavutettavat tiedonsiirtonopeudet yltävät 1 Gb/s asti. Kapasiteetin kasvattamiseksi on julkaistussa kirjallisuudessa esitetty taajuusalueen laajentamista yli 100 MHz:n taajuuksille. Tässä diplomityössä esitetään empiirinen tutkimus korkeataajuisen sähköverkkotiedonsiirron aiheuttamasta säteilystä. Korkeiden taajuuksien käyttö sähköverkkotiedonsiirrossa aiheuttaa haitallista säteilyä, joka täytyy ottaa huomioon ennen kuin taajuusaluetta voidaan laajentaa. Työssä saavutetut tulokset osoittavat kuinka sähköverkon eri komponentit vaikuttavat kokonaissäteilyyn kun yli 100 MHz:n taajuuksia käytetään sähköverkkotiedonsiirrossa. Tulokset osoittavat että tyypillisen talon tai toimistorakennuksen sähköverkossa siirretyn korkeataajuisien signaalin vuotama säteily saavuttaa maksimitasonsa 300 MHz:n taajuuteen mennessä ja ei kasva sitä korkeammilla taajuuksilla. Säteilyn maksimitasot ovat noin 13 dB EN55022 standardin rajojen yläpuolella taajuuksilla 230 MHz – 1000 MHz kun sähköverkkoon syötetyn signaalin tehollinen tehotiheys on -80 dBm/Hz. Tuloksia voidaan käyttää hyödyksi laajempia mittauskampanjoita suoritettaessa kansallisten tehorajoitusten päättämiseksi kun UHF ja sitä korkeampia taajuuksia käytetään sähköverkkotiedonsiirrossa.

Avainsanat: sähkömagneettinen yhteensopivuus, sähkökaapeli, simulaatio, mittaukset.

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FOREWORD

The main contribution of this Master's Thesis was to find out how the components of a power line system will radiate when high frequencies are utilized in an in-house or in-office power line communication system. The main results were published in a conference paper at the EMC Europe 2014, Gothenburg. This thesis was based on the 3D EM simulation models developed in earlier research project in 2012-2013 at the Centre for Wireless Communications (CWC), University of Oulu.

I would like to present my gratitude to Juha-Pekka Mäkelä and Risto Vuohtoniemi for their inspiration, support and patience in making this thesis and all the projects leading towards it.

Oulu, April 21, 2019

Tarmo Ronkainen

LIST OF ABBREVIATIONS AND SYMBOLS

AMN	artificial mains network
ANSI	American national standards institute
BPL	broadband over power line
CEN	European committee for standardization
CENELEC	European committee for electrotechnical standardization
CISPR	international special committee on radio interference
CSMA-CA	carrier sense multiple access with collision avoidance
CST	Computer Simulations Technology
EM	electromagnetic
EMC	electromagnetic compatibility
EMI	electromagnetic interference
ESO	European standards organization
ETSI	European telecommunications standards institute
EU	European Union
EUT	equipment under test
FCC	federal communications commission
FIT	finite integration technique
ICT	information and communications technologies
IEC	international electrotechnical commission
ISO	international organization for standardization
ISP	inter-system protocol
ITE	information technology equipment
LAN	local area network
L	live
LV	low voltage
MAC	media access control
MIMO	multiple-input multiple-output
MV	medium voltage
N	neutral
OATS	open area test site
OFDM	orthogonal frequency division multiplexing
PAM	pulse amplitude modulation
PE	protective earth
PEC	perfect electric conductor
PHY	physical layer
PLC	power line communications
PLCP	physical layer convergence protocol
PSD	power spectral density
PVC	polyvinyl chloride
QAM	quadrature amplitude modulation
QC-LDPC	quasi-cyclic low-density parity-check
QPSK	quaternary phase shift keying
SNR	signal-to-noise ratio
STF	special task force
TDMA	time division multiple access
TR	technical report
TS	technical specification

k	conductor twist rate
P_{out}	output power of the signal
R_{bw}	bandwidth of the analysis filter
ε_{r}	relative permittivity

1 INTRODUCTION

The data rate requirements in the world are constantly growing. This is due the increasing number of people, different classes of devices and new technologies, e.g. current 5G development, that utilize the wired or wireless networks to transfer more and more data. All new areas of possible innovations and improvements need to be explored including maximally utilizing the existing infrastructure for communications. One of the most widely spread infrastructure are the power lines, which we can harness to transfer data with a technology called power line communications (PLC).

PLC has traditionally been considered as low frequency band and relatively low data rate technology. The obtained data rates from the power line transceivers have over the past decade increased tremendously providing sufficient usage experience for high data rate applications like high definition video viewing or interactive gaming. The low voltage in-home and in-office power supply grids can be observed as an interesting alternative and complementary technology for wireless communication applications varying from, e.g., low data rate control signaling to high data rate multimedia distribution [1]. The utilization of smart grids and new applications for domestic and industrial use has drawn the attention of both academic and industry researchers to study different methods to further increase the available data rate. Utilization of higher frequencies is one alternative to increase capacity of PLC, e.g., for shorter distances.

Since power line cables were not designed to carry high frequency communication signals, they give rise to radiated emission that may interfere with other communication systems within the occupied spectrum. The PLC systems should be designed with care so that from an electromagnetic compatibility (EMC) point of view, PLC communication systems must not cause any electromagnetic interference (EMI) to broadcasting or communications systems and vice versa. The specific emission limits are subject to national regulations. The electromagnetic radiation of PLC has been studied widely for frequencies below 100 MHz [2],[3],[4] and PLC standards [5],[6],[7],[8] have adopted these studies for defining the Power Spectral Density (PSD) mask that the signals inside the power line must comply.

Higher frequencies, however, have been given much less attention when interference radiation measurement studies are carried out. Studies have shown that the frequency range that can be utilized for in-home or in-office PLC can reach up to 600 MHz based on the attenuation of the power line network [9],[10]. In this thesis, the radiated interference analysis of the elements of power line networks (i.e. plugs, sockets and cables) in the 100 MHz – 1000 MHz frequency range is analyzed. The current status of broadband PLC specifications and standards are presented in Chapter 2. The EMC standards, limits and the methods of measurement for PLC are presented in Chapter 3. The Chapter 4 describes a 3D electromagnetic (EM) simulation model and results for the radiated interference. The EMC chamber measurements are presented in Chapter 5. The Chapter 6 includes analysis of the obtained results and provides discussion for future work. The summary of the work is given in Chapter 7.

2 BROADBAND PLC SPECIFICATIONS AND STANDARDS

Historically, the broadband PLC specifications have been developed by groups of companies, i.e. industry alliances, as well as individual companies with aim to promote widespread adoption of the technology. The formal standardization process has been slower and often feeding from the industry specifications [11]. This chapter presents the most wide spread current PLC industry specifications and international standards. Also, the European ETSI and CENELEC activities related to development of PLC are described shortly.

2.1. Industrial Specifications on Broadband PLC

Two of the most active industrial groups developing broadband PLC specifications in recent years have been the HomePlug Alliance and HD-PLC Alliance. HD-PLC is popular in Japan where as HomePlug specifications are utilized worldwide.

2.1.1. HomePlug Alliance

HomePlug specifications are developed by several industry participants in the HomePlug Alliance Technical Working Group [5]. The group was formed in April 2000. The founding members of the group included 3Com, AMD, Cisco Systems, Compaq, Conexant, Enikia, Intel, Intellon, Motorola, Panasonic, S3’s Diamond Multimedia, Tandy/RadioShack and Texas Instruments [11]. Currently, the group has about 60 member companies (2014) [5]. The first specification released by the group, HomePlug 1.0, offered a 14 Mbps physical layer (PHY). Orthogonal Frequency Division Multiplexing (OFDM) was utilized with 84 carriers in the 4 – 28 MHz frequency range. Some frequencies were masked due to regulatory constraints in order to avoid interference with existing services in this frequency band. The signal was modulated with Binary Phase Shift Keying (BPSK) or Quaternary Phase Shift Keying (QPSK) techniques depending on the channel quality. Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) was used as a Media Access Control (MAC). [11]

A next generation HomePlug AV 1.0 specifications were published in 2005 with improved transmission rates up to 200 Mbps. A wider bandwidth, 1.8 – 30 MHz, was utilized with bit loaded OFDM with 1155 sub-carriers. A BPSK, QPSK, 8-Quadrature Amplitude Modulation (QAM), 16-QAM, 64-QAM, 256-QAM or 1024-QAM modulation was used depending on measured signal-to-noise Ratio (SNR) at the carrier frequency. A hybrid CSMA Time Division Multiple Access (TDMA) was utilized as a MAC. Other improvements included flexible frequency notching, long symbol time to minimize guard interval overhead, convolutional turbo coding and synchronization to the AC frequency cycle. [11]

HomePlug AV2 specifications were released in September 2013 with additional 30 MHz – 86 MHz frequency band and higher order modulation schemes up to 4096-QAM. HomePlug AV2 utilizes multiple-input and multiple-output (MIMO) technique where all three wires of the in-wall cable are used to transfer data in different pairs simultaneously (e.g. live-neutral and live-ground wires) [12]. The transmission rate increased up to 1.5 Gbps. The HomePlug AV specifications are probably the most widely utilized broadband PLC technology worldwide [13].

2.1.2. HD-PLC Alliance

HD-PLC Alliance was founded by Panasonic Corporation in September 2007 and consists of voluntary groups based mainly in Japan. The HD-PLC technology utilizes Wavelet-based OFDM where the rectangular/raised-cosine windowing used in conventional FFT-OFDM is replaced with critically decimated Perfect Reconstruction Cosine Modulated Filter Banks. The advantage of Wavelet-OFDM is the reduced need for guard intervals between consecutive symbols and improved adjacent carrier attenuation (up to 35 dB) to support regulatory constraints. 512 carriers are used with Pulse Amplitude Modulation (PAM). The HD-PLC operates in the 2 MHz – 28 MHz frequency range. CSMA/TDMA is used as a MAC. RS and convolutional codes are used in error correction scheme. [11]

HD-PLC supports dynamic frequency nothing by periodically sensing for e.g. short wave radio broadcast signals to avoid interference. The power of the signal is also dynamically reduced if maximum signal level is not needed for good performance. Adaptive bit loading is used based on channel quality. The maximum achievable transmission rate is 240 Mbps. [7]

2.2. International Broadband PLC Standards

International standards that have been developed for broadband PLC include the IEEE 1901 standard and the ITU-T G.hn standard. The IEEE 1901 is mainly based on the existing PLC technologies developed by industrial organizations. The ITU-T G.hn standard is supported by the Home Grid Forum and its members [8].

2.2.1. The IEEE 1901 Standard

IEEE P1901 working group was established in 2005 with a goal to unify PLC technologies and to develop an interoperable international standard. The group's members include corporations, government agencies, trade associations, universities and standard developing organizations. The IEEE 1901-2010 standard for broadband over power line networks was released in December 2010 [6]. The standard defines three PLC technologies:

- FFT-based OFDM PHY/MAC (HomePlug AV 1.0 compatible).
- Wavelet-based OFDM PHY/MAC (HD-PLC compatible).
- ITU-T G.hn compatible PHY/MAC.

The FFT-based OFDM operates in the 1.8 MHz – 50 MHz frequency band. The Wavelet-based OFDM uses the frequency band from 1.8 MHz – 28 MHz with optional upper band up to 50 MHz depending on country regulations. The coexistence and interoperability of the different technologies is handled through the Inter-System Protocol (ISP) and a common MAC which can control different PHYs with a Physical Layer Convergence Protocol (PLCP). The maximum transmission rate is in the order of half a Gbps. [11]

The IEEE 1901 standard defines a PSD limit mask that the signals injected in the power line must not exceed. The PSD limit is defined as -55 dBm/Hz in the 2 MHz – 30 MHz frequency band and decreases to -85 dBm/Hz in the 30 MHz – 50 MHz frequency band. Notches for amateur radio spectrums are also included. [6]

2.2.2. The ITU-T G.hn Standard

ITU-T G.hn standard is aiming for development of unified connectivity over multiple home wiring networks including coaxial, phone line, data and power line cables. The development of the standard was started in 2006 [11]. The G.hn utilizes windowed-OFDM PHY as specified in ITU-T Recommendations G.9960 and G.9961 [14]. The standard defines different set of parameters for different types of medium, e.g. the number of subcarriers and subcarrier spacing for the OFDM or the coding rates are media depended. For power lines, 4096 carriers are utilized with up to 4096-QAM modulation schemes. The frequency range for power line is specified as 2 MHz – 100 MHz with an optional pass band in the 100 MHz – 200 MHz frequency band. The G.hn standard utilizes a quasi-cyclic low-density parity-check (QC-LDPC) coding [11].

Similar to the IEEE 1901 standard, the PSD limit mask of G.hn for power line cables is -55 dBm/Hz between 2 MHz – 30 MHz. The limit decreases to -85 dBm/Hz in the 30 MHz – 100 MHz frequency range [15]. The PSD limits are presented in Table 1 and Figure 1 without regulatory notches and EMC requirements (e.g. for amateur radio, FM-radio).

Table 1. Typical PSD limits for broadband PLC

Frequency range (MHz)	**PSD limit (dBm/Hz)**
1.8 to 30	-55
30 to 100	-85

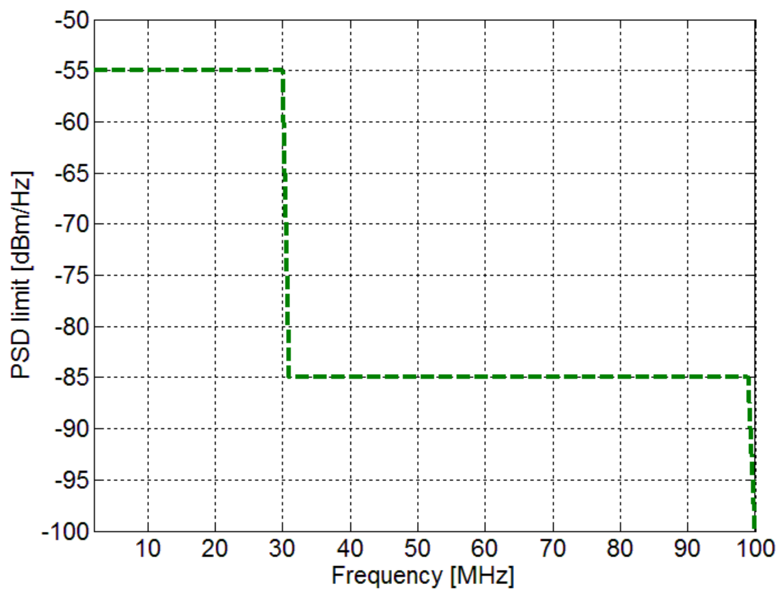


Figure 1. Typical PSD limits for broadband PLC.

2.3. ETSI and CENELEC Standardization for PLC

The European Union (EU) recognizes three European standards organizations (ESOs): European Committee for Standardization (CEN), European Committee for Electrotechnical Standardization (CENELEC) and European Telecommunications Standards Institute (ETSI) [16]. The objectives of the organizations can be categorized in to two groups: (a) market growth (standards for inter-working equipment between manufacturers) and (b) regulatory (electrical safety and EMC). Currently there are no PLC related activities in CEN [11].

ETSI is a non-profit organization with 750 member organizations from 63 countries (2014). ETSI produces globally-applicable standards for Information and Communications Technologies (ICT). The main technical achievements of ETSI include technologies such as GSM, the SIM card, xDSL and DVB [18]. CENELEC was established in 1973 and it has members in 33 countries and affiliates in 13 countries [17].

2.3.1. ETSI TC PLT

The organization of ETSI is divided in Technical Committees (TC). ETSI TC PLT (Power Line Telecommunications) was established in October 1999. It produces Technical Reports (TR) including measurements, field tests and recommendations, and Technical Specifications (TS) which can include, e.g., standardized test methods. The work is assigned in Special Task Forces (STF). Currently active operations (2014-2015) include 4K Video and High Speed Internet Services transmission over MIMO-PLT (STF 468) and Short Range Powerline modems for Very High Bit Rate links for HDMI 2.0 interfaces (STF 477). ETSI TC PLT co-operates with ETSI TC EMR (EMC and Radio Spectrum Matters), PLC Forum and CENELEC SC205A. [18]

2.3.2. CENELEC SC205A

CENELEC Technical Committee 205 was established to develop home and building electronic systems. The work covers intelligent systems and home automation and also electrical safety and EMC aspects. The Sub-committee 205A focuses on mains communication system (i.e. PLC). The main purpose is to define standards which will comply with existing regulation including radiated and conducted emissions, co-existence with different systems and methods of measurements in lower frequency bands (i.e. for narrowband PLC used in home automation systems). [17]

3 INTERNATIONAL EMC STANDARDIZATION AND LIMITS

In general, PLC devices and installations are classified as information technology equipment (ITE) and thus must comply with appropriate international EMC standards. In Europe the radiated interference limits are controlled by the CENELEC EN 55022 standard [19]. In the USA the EMC limits are regulated according to the Federal Communications Commission (FCC) requirements [20]. The IEEE 1775-2010 standard provides measurement guidelines and specifications for PLC equipment and installations [21].

3.1. CENELEC EN 55022

The CENELEC EN 55022 standard applies to all ITE excluding the radio transmission and/or reception equipment. The standard defines limits and methods of measurement for conducted and radiated disturbance. The information presented in this thesis covers radiated disturbance part of the standard.

3.1.1. General measurement conditions

The general measurement conditions of the standard state that the equipment under test (EUT) must be configured, installed, arranged and operated in a manner consistent with typical applications and installations. The EUT position to ground plane should present a typical configuration, i.e. tabletop equipment is placed on non-conductive table and floor standing equipment on ground (insulated). If EUT is intended to be used in a wall-mounted installation, the EUT is regarded as tabletop equipment with orientation presenting typical installation practice. The mains power cable(s) of the EUT is placed to drape ground reference plane. The connections to mains power outlets must not protrude above the ground plane. If an artificial mains network (AMN) is used, it is installed under the ground plane. In case EUT requires a dedicated ground contact, a connection should be made to the ground plane. If a system consists of multiple units, the configuration is made to form a minimum representative configuration. At least one port of the different types of interface connections of the EUT needs to be connected to a cable, load or device.

3.1.2. Tabletop equipment

The tabletop arrangement consists of a non-conductive table, nominally 1.5 m long and 1.0 m wide, but can be larger depending on the size of the EUT. The table height is 0.8 m above the ground plane as presented in Figure 2. If the EUT consist of the multiple units, they are placed nominally at a 0.1 m distance of each other. If the units are stacked, they should be directly on top of each other. The cables between the units are set to drape freely on the back of the table, but no closer than 0.4 m from the ground plane. Excess cables must be bundled if needed at the cable center in a bundle no longer than 0.4 m. Any controlling units, such as mouse or keyboard, are placed on the table representing typical configuration. The ends of the signal cables connected to EUT that are not connected to any other unit need to be terminated. The cables from the EUT that connect to equipment outside the test site are placed on the floor. If the EUT is equipped with an external power supply, it is placed on the table if the mains cable is longer than 0.8 m. In case the mains power cable is shorter, then the power supply is placed above the floor so that the mains cable is fully extended vertically. If the power supply is integrated in the mains power plug, the supply is placed on the table and an extension power cable is used to connect the power.

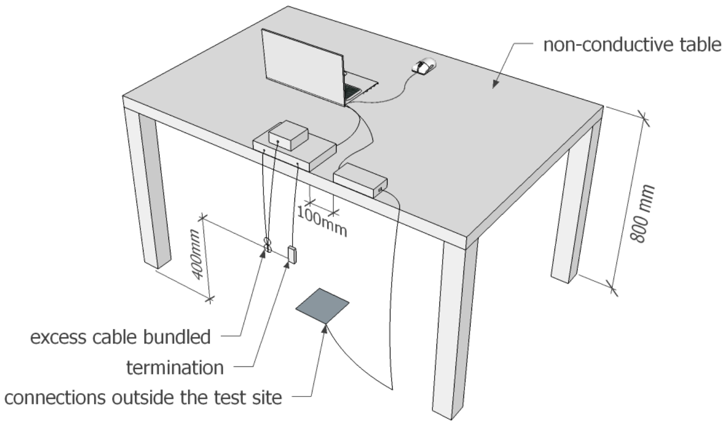


Figure 2. Placement of tabletop equipment on a non-conductive table.

3.1.3. Floor standing equipment

Floor standing equipment is placed on top of the ground plane separated insulation material with thickness up to 15 cm. The equipment must not have direct metallic contact to the ground plane. The cables are similarly insulated from the ground plane and are placed on the floor. Excess cable must be bundled at the cable center in a bundle no longer than 0.4 m or arranged in a serpentine form. If the EUT consists of multiple units, the cables between units are placed at least 0.4 m above the ground planed and bundled if necessary. In case the connectors of the units are closer than 0.4 m to the ground plane, then cables are placed at the connector height as presented in Figure 3.

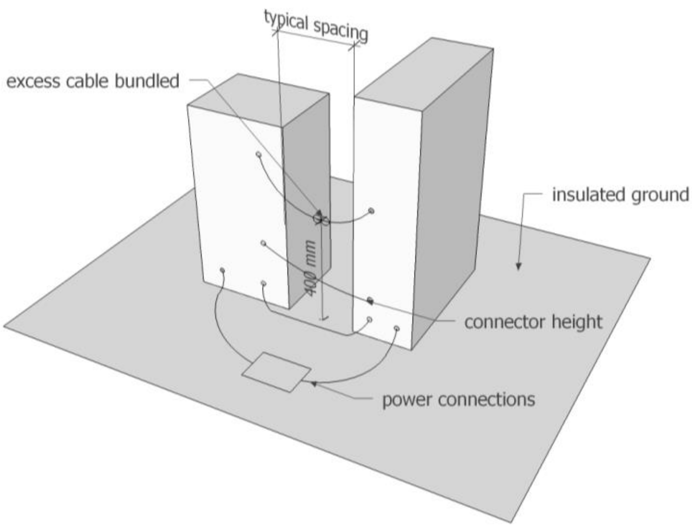


Figure 3. Placement of the units and cables of floor-standing equipment.

For a combination of the tabletop and floor-standing the equipment, the distance between the units is set to present a typical installation spacing as presented in Figure 4. The configuration and placement for cables and connections are as described previously.

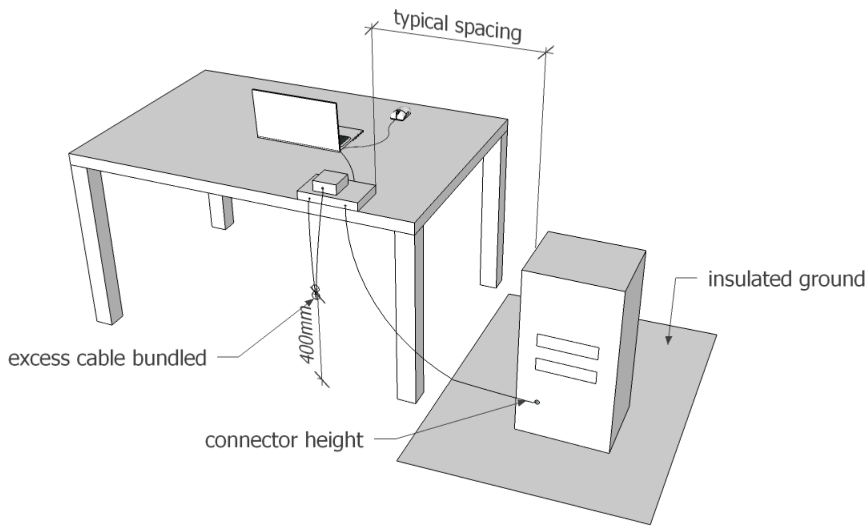


Figure 4. Placement of the units and cable for a combination of tabletop and floor-standing equipment.

3.1.4. Operation of the equipment under test

The operation of the EUT during the measurement is determined by the manufacturer with highest expected emission levels in a typical use. The EUT is operated with nominal voltage and typical loads (electrical or mechanical). Actual loads should be used whenever possible and any mechanical activities of the EUT should be performed. The test program needs to be designed and performed in a manner that the different parts of the EUT are activated (e.g. write/read operations of the disk/memory) and highest emissions levels are captured. The test procedure and configuration of the EUT needs to be described in the test report so that the results can be repeated.

In case the EUT is a subpart of a larger system, i.e. data processing terminals or a distributed network, it can be tested independently. For example, in a case of local network (LAN), the lengths of cables can be arranged in a measurement site and the connecting ITE equipment outside so that they do not contribute to measured level of disturbance. If the EUT interacts with another ITE for its functionality, e.g., a power interface, the interfacing ITE or a simulator should be included in the measurement to have a representative configuration of a typical usage. The effects of the interacting ITE or a simulator have to be able to be isolated or identified. In case the EUT itself is a host unit for another ITE, the interfacing ITE should be included in the measurement. If a simulator is used instead of a actual interfacing ITE, it should accurately represent the mechanical or electrical loads of the ITE (e.g. RF impedances).

3.1.5. Measurement conditions for radiated interference testing

During the measurement of radiated disturbance, the ambient noise needs to be at least 6 dB below the specified limit. In case the combined ambient noise and EUT noise is below the limit, the EUT is considered to satisfy the regulation. If the combined radiation level is above the limit, the EUT is not considered to fail the test unless two conditions are met: a) the ambient noise level is at least 6 dB below the combined radiation level and b) the ambient noise level is at least 4.8 dB below the limit. Initial testing should be performed to find out the frequencies of highest disturbances and the corresponding configuration and operation mode of the EUT. In case the reading fluctuates close to the limit, the levels should be monitored for at least 15 seconds at the each measurement frequency. The highest reading should be recorded, but any brief high isolated radiation levels should be ignored. The frequency range of the measurement is determined by the highest frequency of the EUT internal source or the operational frequency of the EUT. The corresponding measurement frequencies are presented in Table 2.

Table 2. The highest measurement frequency of radiated disturbances depending on frequency range of EUT internal sources

Highest frequency of EUT internal sources	**Highest measurement frequency of radiated disturbance**
less than 108 MHz	1 GHz
108 MHz to 500 MHz	2 GHz
500 MHz to 1 GHz	5 GHz
above 1 GHz	up to 5 times the highest frequency or 6 GHz whichever is less

The testing for radiated disturbance is made on either a) a sample of equipment using a statistical evaluation given in EN 55022 standard [19] or b) on one equipment only in which case the subsequent tests are necessary on equipment taken on random from production. If at least 80 % of the produced equipment satisfies the limit with at least 80 % confidence, the production is considered to be in accordance to the standard.

The required measurement instrumentation is specified in CISPR 16-1-1 [22]. A quasi-peak detector is utilized in measurement between 30 MHz and 1 GHz. A peak measurement detector can be used to save measurement time. However, the measurements with quasi-peak detector are considered to take precedence in case of a dispute. The measurement ranges and corresponding detector bandwidths can be seen in Table 3. A comparison between different detector types with a low, medium and high frequency signal is presented in Figure 5.

Table 3. Measurement bandwidths for radiated disturbance

Measurement range	**CISPR band**	**Measurement bandwidth (-6 dB)**
9 kHz – 150 kHz	A	200 Hz
150 kHz – 30 MHz	B	9 kHz
30 MHz – 1 GHz	C/D	120 kHz
above 1 GHz	E	1 MHz

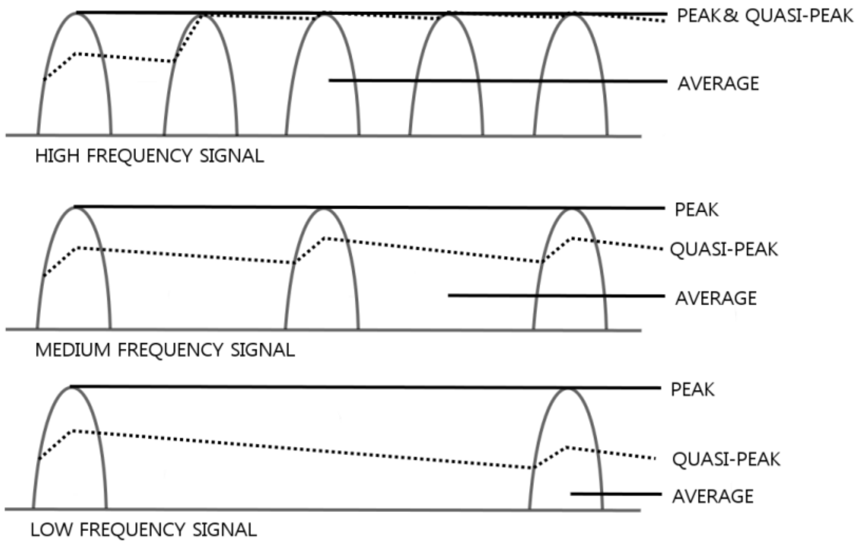


Figure 5. Average, peak and quasi-peak detector.

The recommended antenna specified in CISPR 16-1-4 is a balanced dipole antenna for measurement below 1 GHz [23]. Other antennas can be used if the results can be correlated with a balanced dipole antenna. The measurement distance is specified as a distance between the marked measurement center point of the antenna and an imaginary circle enclosing the EUT (e.g. including sub-devices and interconnecting cables). The limits specified in EN 55022 are given for 10 m measurement distance. If the 10 m distance is impractical, measurement can be made at a 3 m distance with an inverse proportionality factor of 20 dB per decade. However, measuring large EUTs from 3 meters distance can cause measurement errors due the near field effects. The layout for radiated emission test can be seen in Figure 6. The antenna height is adjusted between 1 m and 4 m and the EUT is rotated to find out the direction of the maximum radiation at each test frequency. Also the antenna polarization is tested (horizontal/vertical).

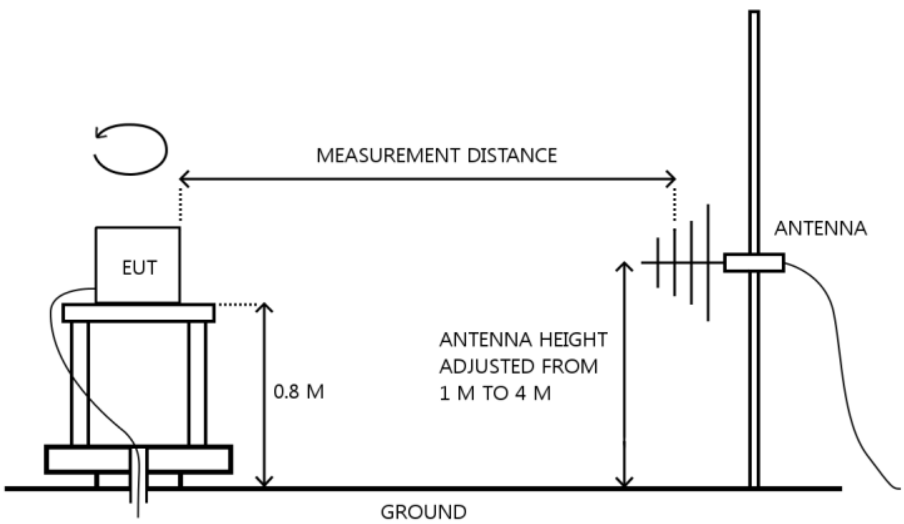


Figure 6. The layout for a radiated emission test.

The measurements are done in an open area test site (OATS) or an alternative test site, e.g., anechoic chamber. The requirements for a test site are specified in CISPR 16-1-1. The test site has to be flat and have no overhead wires or reflecting structures inside an elliptical area seen in Figure 7. The elliptical area has a major diameter (MD) of $2R$ and a minor diameter (mD) of $R\sqrt{3}$, where R is the measurement distance.

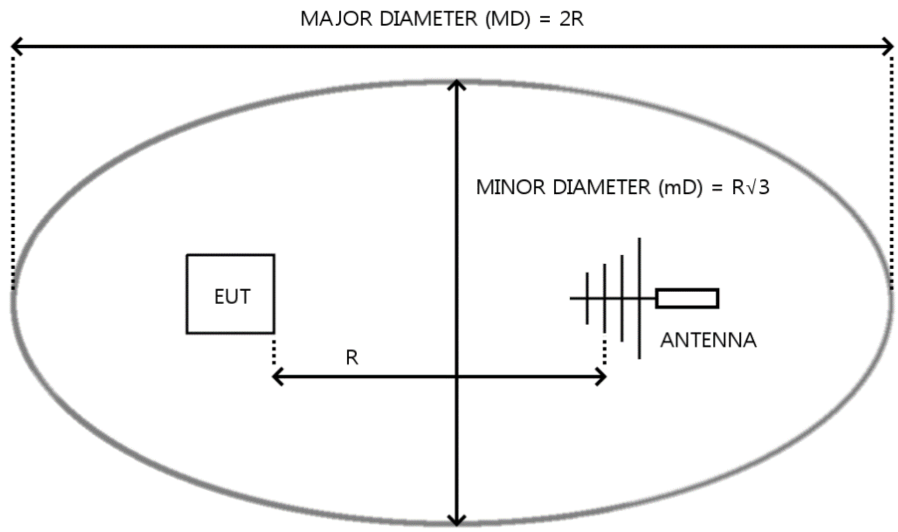


Figure 7. The boundary area of the test site to be free of reflecting objects.

The test site has to be equipped with a conductive ground plane. The minimum size of the ground plane can be seen in Figure 8 where d is the maximum test unit dimension, a is the maximum antenna dimension, D is d + 2 m, W is a + 2 m and L is the measurement distance (3 m or 10 m). The ground plane needs to cover at least 1 m beyond the imaginary circle enclosing the EUT and the area between the EUT and the antenna. The ground plane has to have no holes or gaps larger than one tenth of the wavelength of the highest measurement frequency.

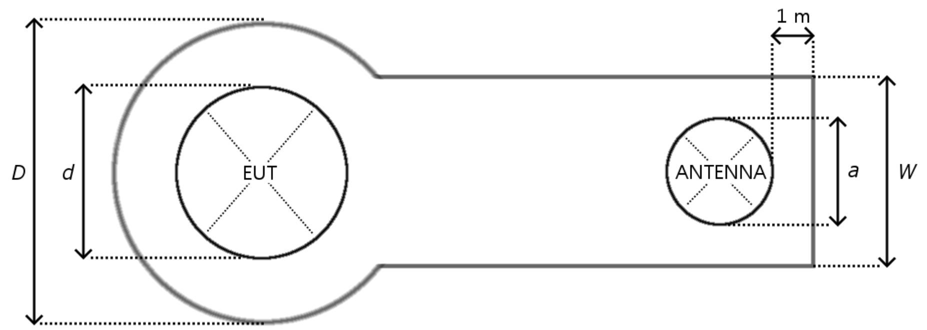


Figure 8. The minimum size of the conductive ground plane.

3.1.6. Limits for the radiated interference

Two equipment classes are defined by the standard, a Class A and a Class B. Class A includes equipment intended for industrial use and shall have a warning label: *This is a class A product. In a domestic environment this product may cause radio interference in which case the user may be required to take adequate measures.* Class B equipment is intended for domestic, i.e. home or office, use. The domestic environment is defined as an environment where radio or broadcast devices can be within 10 meters distance.

The quasi-peak radiation limits specified in the EN 55022 standard for Class B devices can be seen in Table 4. The limits are given for 10 meters measurement distance [19]. The limits can be interpolated to 40 dBμV/m and 47 dBμV/m respectively for a 3 meters measurement distance [2].

Table 4. CENELEC EN 55022 Class B radiation limits

Frequency range (MHz)	Electric field strength (dBμV/m)	Measurement distance (m)
30 to 230	30	10
230 to 1000	37	10

3.2. FCC Title 47 Part 15

The Part 15 of FCC Title 47 [20] sets the regulation for an intentional, unintentional or incidental radiator that can be operated without individual license. Also, technical specifications, administrative requirements and conditions for marketing of the devices are provided. Unless the intentional or unintentional radiator is in accordance to these regulations, it must be licensed. PLC equipment and installations are regarded as intentional radiators.

The radiated emissions from the devices under the scope of Part 15 must not exceed the specified limits under any conditions. The equipment must be constructed in a way that any adjustments that are accessible to the user must not cause violation of the regulations. The instructions and certification for access broadband over power line (BPL) equipment must include the appropriate installer and user settings that are required for the installation to be in conformance to the regulation. Instructions to users should also include advice to resolve any harmful interference problems. The operators of the part 15 devices are required to cease operation in case any harmful interference to the authorized radio spectrum users occurs. In the following, the main measurement conditions and limits for the radiated interference are presented.

3.2.1. General measurement conditions

The measurements of intentional and unintentional radiators are performed in accordance to the ANSI C63.4 [24]. Similarly to recommendation in CENELEC EN 55022 standard, the measurements are carried over in open area test environment and alternative test sites can be employed in case they provide corresponding results. In a case of the type of equipment that can only be measured at the installation site (e.g. perimeter protection or carrier current systems), the measurement must be made at least at three different installation sites that are representing typical installation practice.

For intentional radiators, the supply voltage is varied between 85 % and 115 % of nominal voltage and the variation if the radiated signal level at the fundamental frequency is measured. In case of a battery operated devices, the measurements are done with a full battery.

The general guidelines for the measurement distance between the EUT and the antenna are similar to EN 55022 standard. For frequencies at 30 MHz and above the measurements can be performed at a different distance than specified in case the near-field effects are taken into account and the measurement equipment is able to detect the signals at a longer distance. However, measurements should not be made at distances longer than 30 meters unless it is demonstrated that measurements at shorter distance are impractical. An inverse proportionality factor of 20 dB per decade is used to compensate for the measurement distance. Measurements are performed in a radial around the EUT to find out the direction of the maximum radiated interference. The EUT is operated in a manner that results in maximum amount of radiation through all the user manageable settings and operation modes. In case the EUT consists of several devices contained in a single enclosure or connected with cables, all of the devices are operated during the measurement. If the EUT has connections to external accessory devices, they are connected during the measurement. In case of a multiple accessory ports, an external accessory device shall be connected to the each type of port. However, only one test with the external accessories connected representing a typical user scenario is required.

The measurements are performed in a frequency range starting from a lowest signal frequency generated within the device (above 9 kHz) and up to frequencies presented in Table 5.

Table 5. The highest measurement frequency of radiated disturbances depending on frequency range of intentional radiator

Highest operational frequency of intentional radiator	**Highest measurement frequency of radiated disturbance**
under 10 GHz	10th harmonic or 40 GHz, whichever is lower
10 GHz to 30 GHz	5th harmonic or 100 GHz
at or above 30 GHz	5th harmonic or 200 GHz

3.2.2. Limits for the radiated interference

The limits for the radiated interference are provided in section Subpart C (§15.209) of the FCC Part 15. The radiation limits are presented in Table 6.

Table 6. FCC radiation limits for intentional radiator (Class B)

Frequency range (MHz)	**Electric field strength (µV/m)**	**Measurement distance (m)**
1.705 to 30.0	30	30
30 to 88	100	3
88 to 216	150	3
216 to 960	200	3

No fundamental emissions are permitted in the 54 MHz – 72 MHz, 76 MHz – 88 MHz, 174 MHz – 216 MHz and 470 MHz – 806 MHz frequency bands. However, the regulation allows exceptions for devices in categories such as biomedical telemetry devices in health care facility, perimeter protection systems, and periodic (non-continuous) signals of e.g. door openers, remote switches and alarms. For example, perimeter protection systems are allowed to operate in the 54 MHz – 72 MHz and 76 MHz – 88 MHz frequency bands within the FCC radiation limits in commercial or industrial applications.

The recommended detector type for measurements below or equal to 1000 MHz is similar to EN 55022, a CISPR quasi-peak detector with related bandwidths. Also, a peak detector may be used in case related factors such as pulse desensitization are taken into consideration and similar measurement bandwidths are utilized. Figure 9 presents a comparison between CENELEC EN 55022 and FCC radiation limits for Class B devices normalized to 3 m measurement distance.

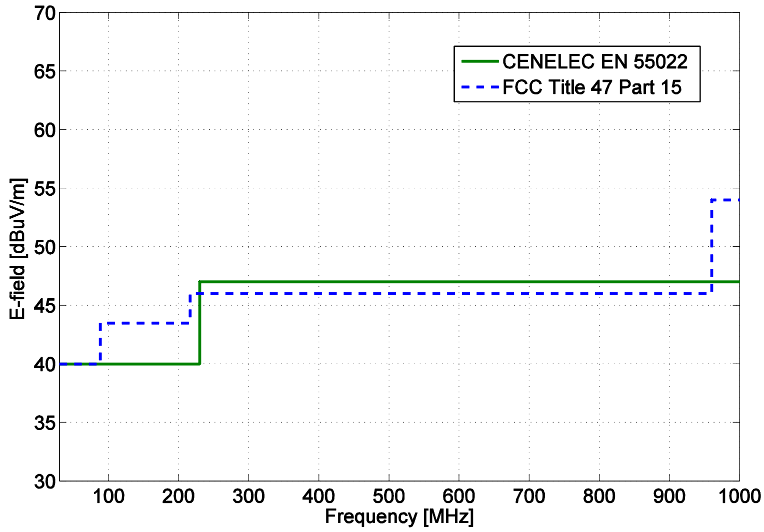


Figure 9. Comparison between CENELEC EN55022 and FCC radiation limits.

3.3. IEEE 1775-2010 Standard

The IEEE 1775-2010 standard presents basic definitions and measurement procedures for PLC equipment and installations. No specific emission limits are given in the standard, as they depend on the national and international regulation. The standard applies for two classes of PLC equipment: Access broadband over power line (BPL), which operates over medium voltage (MV) or low-voltage (LV) power lines and is typically controlled by the electric utility company and in-premises BPL, which utilizes in-home/in-office wiring.

3.3.1. General measurement conditions

The EUT consists of the Access or In-premises installation and the active BPL equipment in the case of in situ measurements. The instructions of the manufacturer are followed to activate and operate the EUT. The measurement case is considered to be applicable only for the specific EUT and installation configuration as the installation may utilize overhead MV, LV or underground wires. The temperature of the environment is recommended to be between 0 ºC to 45 ºC and the humidity is below 75 %. For laboratory measurements, support equipment can be used to fully utilize all the functions of the BPL device(s). The support equipment such as laptop computers must be isolated from the measurement.

3.3.2. Radiated emission testing

Typical BPL equipment may consist of both ITE and BPL parts. If national regulation has separate technical requirements for ITE and BPL equipment, each part should be separately tested. ITE radiated emission testing is performed in an open area test site or in alternative test site, e.g. semi-anechoic chamber, as according to CISPR 16-2-3 procedures [25].

A maximum signal power level of the equipment is applied during the testing. In a case the equipment has adaptive power control, the maximum values are recorded during measurement. For in situ measurements, the equipment is tested with maximum possible power levels by utilizing specific test firmware or software with maximum uplink and downlink burst rate. All operation modes and frequency bands of the equipment are tested. In a case the equipment has controllable settings that affect signal attenuation, the specific setup attained for conformance of the regulation should be noted. A burst rates higher than 20 burst per second are measured with a quasi-peak detector. Lower burst rates are measured with a peak detector.

A biconical, log-periodic or other type of electric-field sensing antenna is used in measurements on above 30 MHz frequencies. Both vertical and horizontal emissions are measured with antenna height adjusted from 1 meter to 4 meters as according to ANSI C63.4 and CISRP 16-2-3 standards. In a case that an overhead MV wires are measured at a distance closer than 10 meters, a qualified person from an electric utility company needs to be consulted. Access BPL emission measurements can be made at 1 meter antenna height as an alternative to varying antenna height. Then additional 5 dB factor is added to the measured field strength values.

3.3.3. In-situ environment

In in-situ environment, the EUT typically consists of In-premises BPL modems for transmitting and receiving signals, the personal computer interface(s) and the LV wiring of the building. The ground level floor of the building is utilized and measurements are performed in a three different sites that represent a typical installation practice of the BPL systems. The connection from the building to external power network can be implemented via overhead or underground wiring. The building or the wiring may not be shielded with metal, unless required by local regulations. The environment needs to have low RF ambient noise characteristics and minimal number of reflecting objects, e.g., vehicles or metallic signs, around the measurement site. The site needs to be at sufficient distance from any powerful radio transmitters or other interfering systems.

The measurements are performed from at least 16 uniformly spaced positions around the building and 10 meter increments from the feeder wire as can be seen in Figure 10. The measurements points are at 10 meters horizontal distance from the building or the feeder. Smaller distances can be used in cases where measurements at 10 meters are not practical. In that case, an appropriate field strength correction is applied. As an alternative testing routine, the antenna can also be freely moved around the building within 10 meter radius to find out the maximum field strengths at any given frequency. The final measurements are then performed with antenna fixed on a tripod.

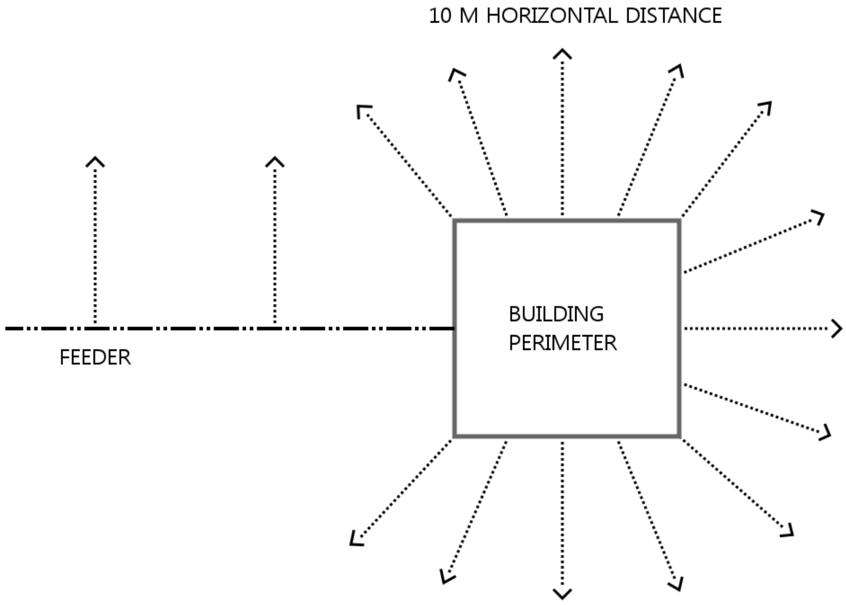


Figure 10. The measurement positions in in-situ environment.

3.3.4. Emission test report and measurement uncertainty

The emission test report needs to include all the relevant information of the testing procedure as according to the ISO/IEC 17025 and ANSI C63.4. In the case of in-situ measurements, detailed description, diagrams and photos about the test environment needs to be provided including, e.g., the surrounding wiring, structures nearby, test antenna positions and geographical information. Other items in the test report can include:

- Detailed information of the EUT, e.g. product and serial numbers.
- Detailed information of the measurement equipment, e.g. calibration data, detector type and bandwidths.
- An explanation of the test procedure including configuration and settings of EUT.
- An explanation of the selection of the test site(s).
- Measured emission levels in dBµV/m compared to relevant limits.
- Field strength levels and frequencies of six highest amplitudes with identified antenna polarization.
- The test results (pass or fail).
- Possible information about the modifications required for the EUT to pass the test.

Methods for estimating measurement instrument uncertainty in radiated emission testing are provided in CISPR 16-4-2 [26]. However, in situ environment presents additional uncertainty problems. Some of the issues may be time variant. A list of issues include, e.g. reflectivity of the ground and obstacles, the geometry of the power cables and RF interference from the surrounding area.

3.3.5. PLC networks typical installations and equipment

The topologies of power line networks can differ greatly depending on, e.g., the location of the installation. Typical MV network topologies include, e.g., a loop ring, radial tree and a mesh network which are illustrated in Figure 11. The topologies can vary depending on the country and regulations therein. The signal can travel through two different paths in a loop ring topology which is the main network type in UK for instance. A radial tree topology typically has a single from source to load and is mainly utilized in the USA and Asia. A mesh network can have multiple signal paths and is popular in large cities in the USA.

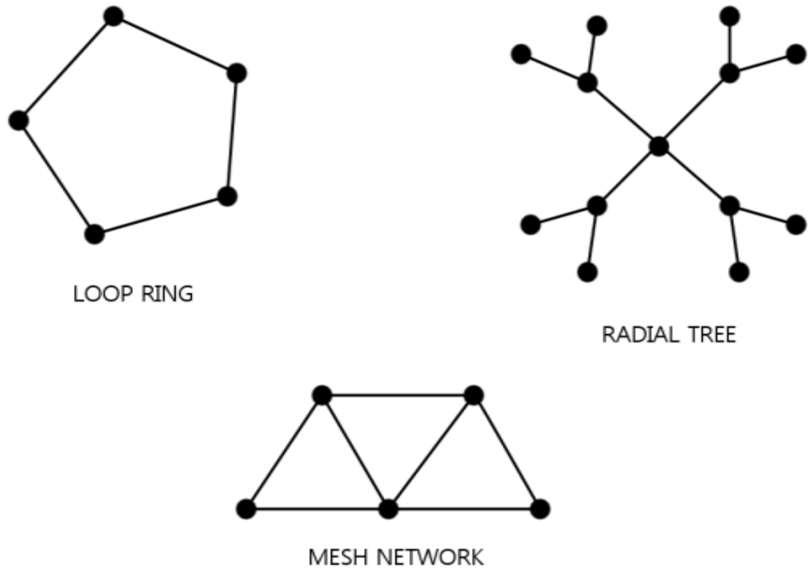


Figure 11. A loop ring, radial tree and a mesh network topology.

The type of cable can have great influence of EMC characteristics of PLC installations. The cables can have different insulation materials, can be with or without a concentric neutral cable and may be twisted or straight. Some of the cables may be underground with different kind of protection constructions applied. The cable impedances can also differ greatly from 20 to 500 Ω depending on the cable type.

Any electrical non-PLC equipment and devices connected to the power line network can cause time-depended variation on the PLC signals and as such affect the radiated interference levels. The main causes are the standing waves created by reflections from impedance mismatches. The non-PLC equipment connected to power line network includes transformers, meters, switches and fuses and typical household devices such as coffee makers, televisions and computers. The power line network also has inherited noise which affects PLC signaling. The main sources of noise are switching power supplies, lamp dimmers and the noise emanating from the corona effect from HV transmission lines. Also the construction type, material and thickness of the walls or floors of the building affect the radiated emission levels.

A classification of ports for PLC equipment can be seen in Figure 12. The PLC device can be divided into two parts, the BPL part and the ITE part. The BPL part contains the power input and the coupler ports. The coupler ports connect to the power line network. The LV coupler port connects to the LV power lines of the building and MV coupler to the MV power lines respectively. The ITE part contains the data signal connection to external devices. All ports are not necessarily present on all PLC equipment.

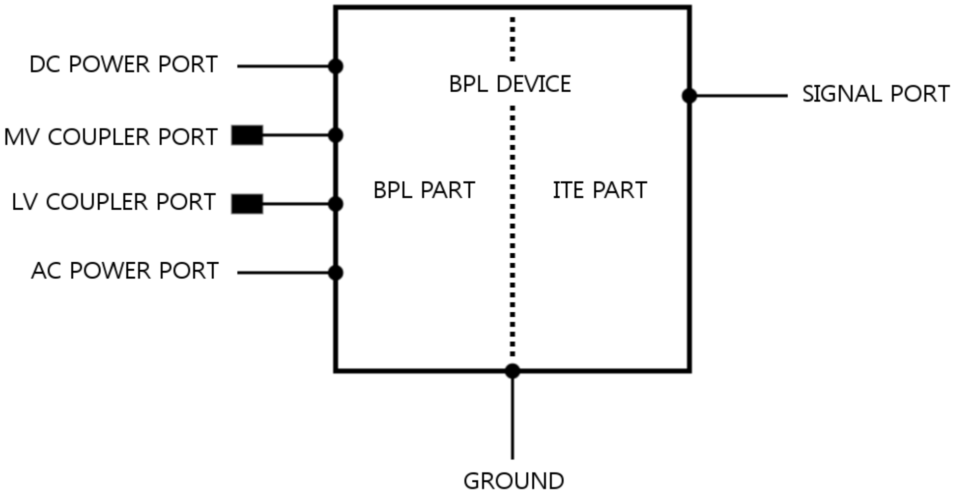


Figure 12. A classification of ports for PLC equipment.

3.3.6. Determining interference caused by PLC systems

The PLC signals typically utilize wideband modulation which makes them difficult to distinguish from the ambient radiation. In the case of in situ testing, the ambient radiation can easily mask the radiated emissions from PLC system. To identify the emissions caused by the PLC systems from the background noise, a few steps could be taken. One is to demodulate the signals that are visible on the EMI analyzer screen which can reveal the interference that are caused by broadcasting or mobile radio systems. Also the typical demodulated sound of the PLC signals can be investigated on a closer distance, with e.g. a clamp on the power line wire, before the actual measurements. Then the sound signature or signal appearance on the receiver screen can then be used in aid to distinguish the interference emanating from the PLC system. The adjustable power level of the PLC signal, in case available as setting, can also be helpful in determining PLC interference. However, the regulated emission levels established for the installation must not be exceeded.

As a general guidance for EMC compatible PLC operation, each installation needs to be assured to satisfy national regulations. Transmitting signals on the frequencies dedicated to licensed radio operators or other users of radio spectrum, e.g. amateur radio, emergency services or aeronautical, should be minimized.

4 RADIATED INTERFERENCE SIMULATIONS

In this section, the PLC radiation is analyzed by utilizing 3D EM simulation. A CST EM simulator [27] is used for the task. First, a brief introduction to calculation domain of 3D EM simulation is given. Then the simulation models for a plug, socket and power line cable are presented. The simulations are first performed for different elements of the power line network to gain understanding on the radiation of different components. Finally, the models are put together as a segment of a power grid and the radiated emission levels are simulated.

4.1. Finite Integration Technique

The finite integration technique (FIT) is commonly utilized in 3D EM calculations. The FIT is a numerical method with a universal spatial discretization scheme. It was first introduced by Weiland in 1976. The FIT is applicable to various EM problems varying from static field calculations to high frequency applications. The calculations can be made in time or frequency domain. FIT discretizes the integral form of Maxwell's equations. A finite calculation domain is defined to solve equations numerically. Mesh system divides the domain into small elements, i.e. grid cells. Orthogonal hexahedral grid system consists of a primary grid and a dual grid. Maxwell's equations are formulated for each of the cell facets separately. Electric grid voltages (**e**) and magnetic faces fluxes (**b**) are allocated in primary grid. The dual grid consists of dielectric faces fluxes (**d**) and magnetic grid voltages (**h**). Figure 13 shows the calculation domain in an orthogonal hexahedral grid system. FIT can also applied to, e.g., tetrahedral or Cartesian grid types. The resolution of the grid has effect on the accuracy of the calculation. Also the material parameters need to be taken into consideration.

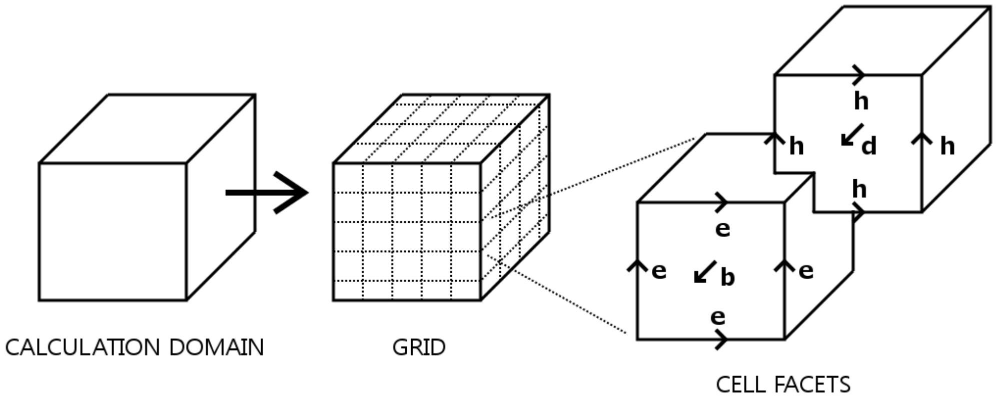


Figure 13. Orthogonal hexahedral grid system.

4.2. Description of the simulation model

3D EM models of a typical plug, socket and in-wall mains cable utilized in Europe are created with CST Microwave Studio software. The designed models, verified material parameters, planned simulation environment and the simulation procedure are presented in the following.

4.2.1. In-wall power line cable

The cable model is based on a typical three-wire cable rated at 16 A of current. The individual wires in the cable are twisted around each other. The wires circulate at the rate of approximately two rounds (720 degrees) per meter. The insulation material of the cable is Polyvinyl Chloride (PVC). Detailed information about the models is given in [9]. A cut-out drawing and a 3D model of the cable is presented in Figure 14.

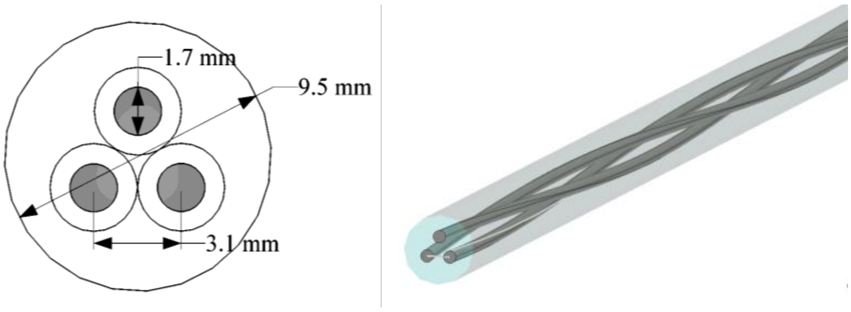


Figure 14. Structure of an in-wall power line cable.

4.2.2. Plug and socket

The plug and socket model is developed based on the Jussi series manufactured by ABB [28]. This type of socket is typically utilized in Finland. An exploded 3D view of the plug and socket model can be seen in Figure 15. The plug model consists of the plastic cover material, the plastic inside of the plug and the conducting metal contacts. The socket model consists of plastic cover material, an insulation material inside the socket, the conducting metal parts of the socket and finally the insulation material at the back of the socket that houses the metal conductors.

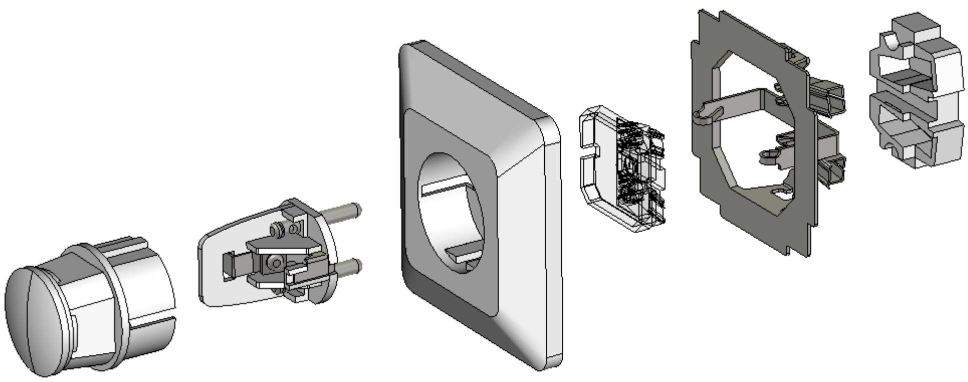


Figure 15. Structure of a plug and socket.

Figure 16 presents how the power line cables connect to the plug and the socket model. The live (L), neutral (N) and protective earth (PE) wires of the cable are connected. The plastic plug cover material is presented as transparent for illustration purposes.

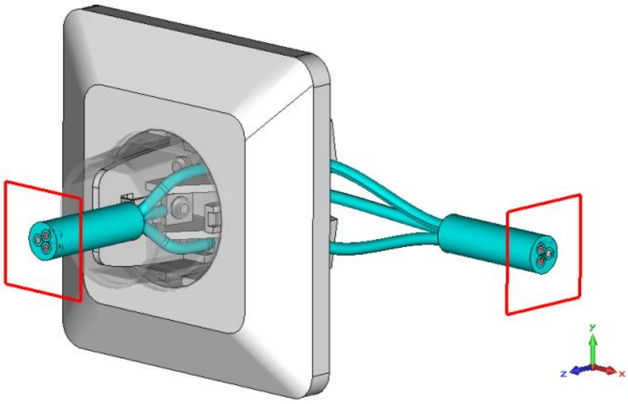


Figure 16. 3D model of a plug and socket with power line cables attached.

4.2.3. Material parameters

The permittivity and loss tangent of the materials can have major effect on the simulation results. The material parameters need to be as accurate as possible. Small pieces of the plastic parts of the plug, socket and cable were measured at the Microelectronics and Materials Physics Laboratory at University of Oulu. The measurements were made with Agilent E4991A RF impedance and material analyzer [30]. The relative permittivity (ε_r) and loss tangent of the materials are calculated from the measurement results. The calculated values are presented in Table 7 [9]. The materials are modelled with Debye 2nd order model n the CST simulation software which takes into account the frequency dependency of the parameters.

Table 7. The measured material parameters of the plug, socket and cable

Material name	Relative permittivity (ε_r)	Loss tangent
Plug cover	3.33	$2.21 \cdot 10^{-4}$
Socket cover	3.67	$5.66 \cdot 10^{-3}$
Plastic inside socket	4.32	$6.14 \cdot 10^{-3}$
Insulation material	6.85	$5.28 \cdot 10^{-2}$
Plastic outside in-wall cable (PVC)	3.24	$1.65 \cdot 10^{-2}$

4.2.4. Simulation environment

The plugs, sockets and wires are placed horizontally above a conducting ground plane. The vertical distance to the ground plane is 1 m. The electric field strength is recorded using a probe at a 3 m distance. The probe is practically a small dot in the simulation environment. The probe is situated 1 m above the ground plane as can be seen in Figure 17. The field strength is captured in the all x, y and z directions and the direction that gives the highest reading is selected in the final results. [29]

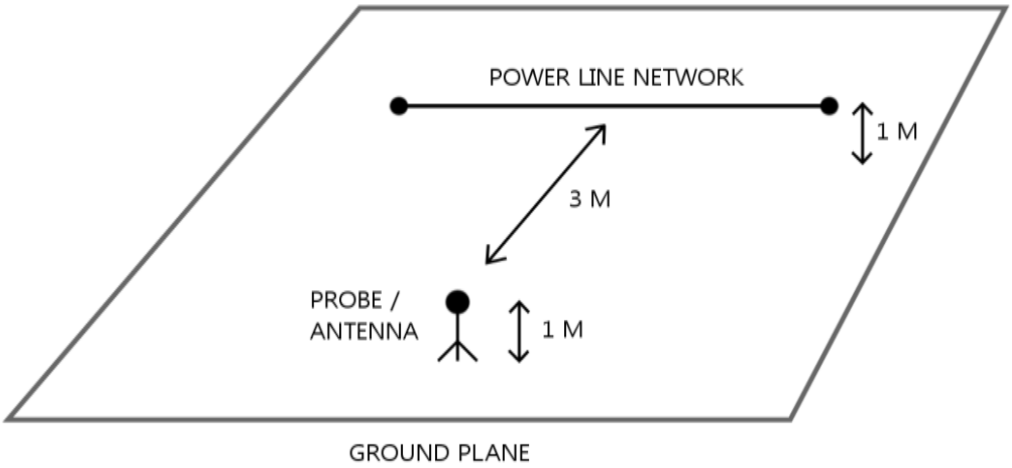


Figure 17. Simulation and measurement model for a power line segment.

Figure 18 shows the 3D view of the simulation environment. The ground plane material is set as perfect electric conductor (PEC) in the simulation software. The ground plane size is set according to the EN 55022 standard.

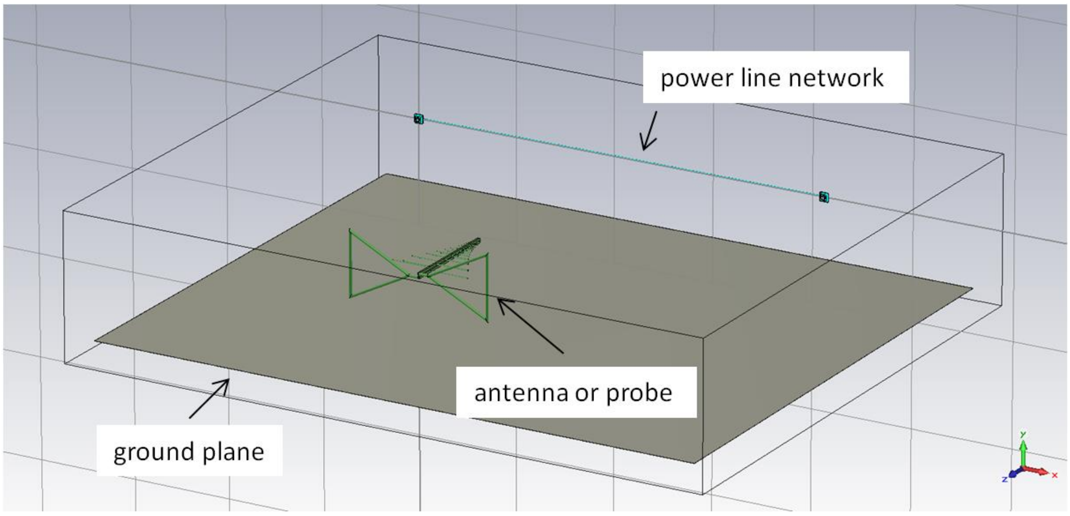


Figure 18. 3D simulation environment.

4.2.5. Simulation procedure

A wideband signal is injected differentially into the two wires of the cable through a 50 ohm port representing a L-N connection mode of the PLC equipment. No signal is applied to the PE-wire of the cable. The system is terminated with a 50 ohm port in the receiving end. The power P_{out} of the signal was adjusted according to the equation

$$P_{\text{out}} = 10 \cdot \log(R_{\text{bw}}) + PS, \tag{1}$$

where R_{bw} is the bandwidth of the analysis filter in Hz and *PSD* is the equivalent Power Spectral Density in dBm/Hz [1]. The analysis filter width for the EN 55022 standard is 120 kHz on frequencies above 30 MHz [19]. The simulation results are presented for an equivalent PSD of -80 dBm/Hz in the 100 MHz – 1000 MHz frequency range unless otherwise specified.

4.3. Simulation results

A comparison between a 3D model of the antenna and a probe is presented first. Then the effect on radiation of different parameters for power line cable is analyzed. Next, the electric field strength caused by the plug and socket as is presented. Finally a full segment of a power line network simulated with plug and socket at the each end of the cable and the results are compared to the limits specified by EN 55022 standard.

4.3.1. Comparison of probe and antenna

In order to justify the accuracy of the simulation results, we first need to evaluate the simulation methodology and find out how accurately we need to model the measuring element in the simulation environment. In real life measurement situation, a measurement antenna is used. However, simulation environment gives us an opportunity to simplify the scenario by introducing a measurement probe that is a mathematical model of the measurement device in the simulation tool. We first test how accurately the probe mimics the antenna behavior. The probe was replaced with a 3D model of a log-periodic antenna used in the measurements to study the effect of the physical size of the antenna. The 3D model of the antenna can be seen in Figure 19.

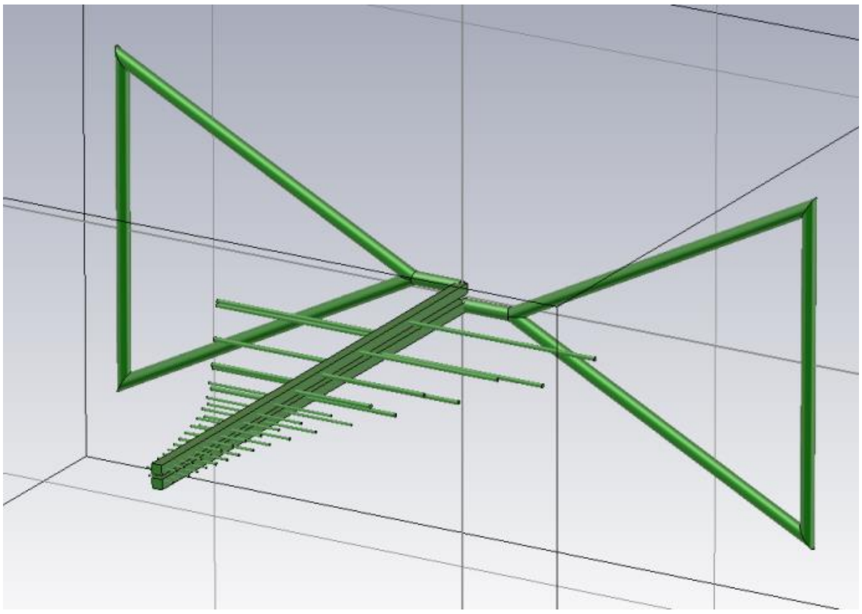


Figure 19. 3D model of an antenna.

After accounting for the antenna factor in the post processing, the results were found to be similar between the antenna and the probe as can be seen in Figure 20. The probe has an advantage of a shorter simulation time due to less complexity in the 3D domain.

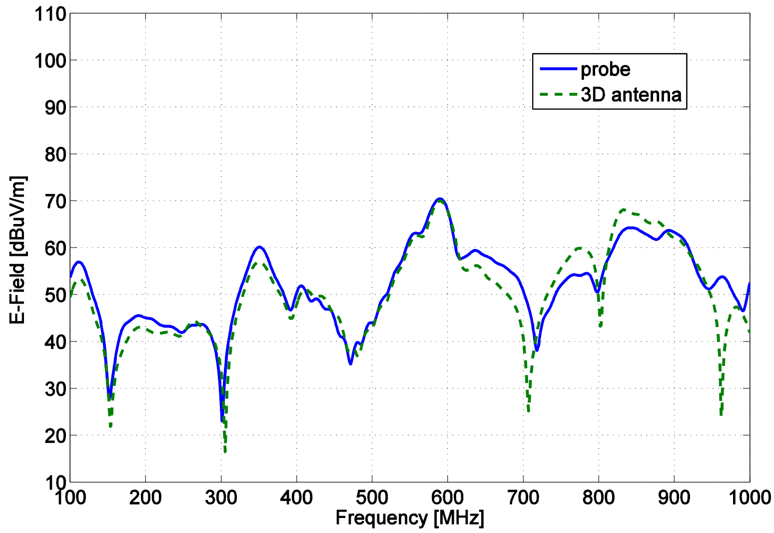


Figure 20. Simulation comparison of probe and 3D antenna model.

4.3.2. Results for power line cable

In order to see the effect of attached structures that are connected to the power line cable, we first simulated a BNC connectors attached to an each end of the 1 m power cable. As the power line cable needs to be attached to BNC connectors during measurements to feed the signal in to the cable, a similar connector is modelled in to the simulation. The 3D model of a BNC connector can be seen in Figure 21.

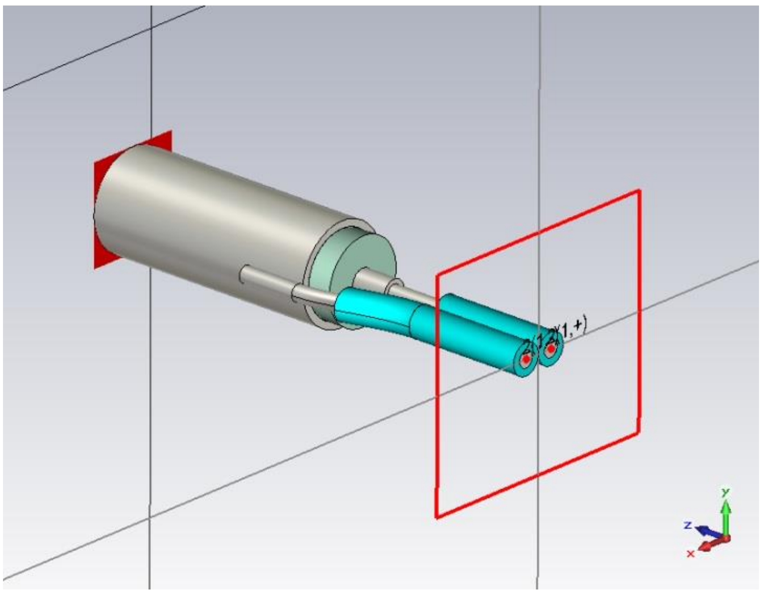


Figure 21. 3D model of a BNC connector.

Figure 22 presents how the BNC connectors contribute to the overall radiation. The power level is increased to -60 dBm/Hz equivalent PSD to make radiation of the cable on low frequencies visible on the graph. We can see that the BNC connectors produce additional radiation on below 750 MHz frequencies compared to the situation where the signal is fed directly inside the power line cable without BNC connectors.

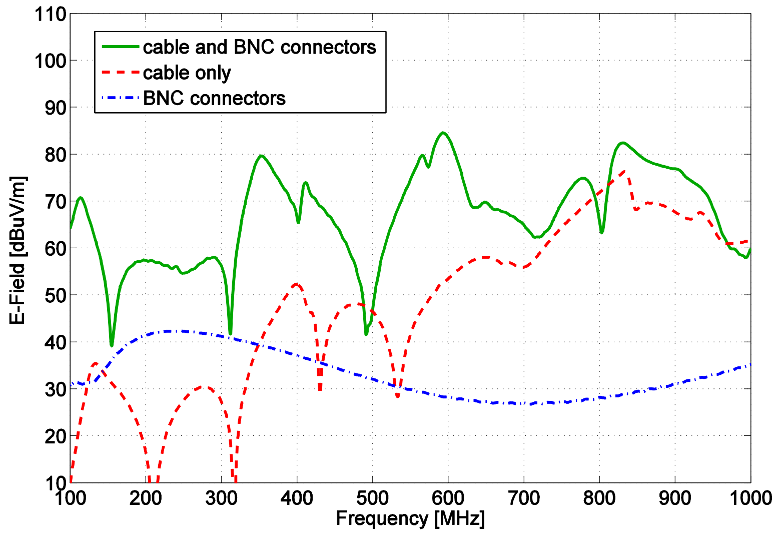


Figure 22. The effect of BNC connectors attached to power line cable to the observed radiation.

The effect of the conductor twisting on the radiation

The effect of conductor twisting of the power line cable on the radiation is analyzed by changing the twist rate (k) of the cable model. The simulated twist rates include 0 (straight), 1, 2 and 3 rounds per meter. Figure 23 presents the simulation results. We can see that the conductor twist rate affects the frequencies of certain dips and peaks in radiation. Overall the average radiation level is unaffected.

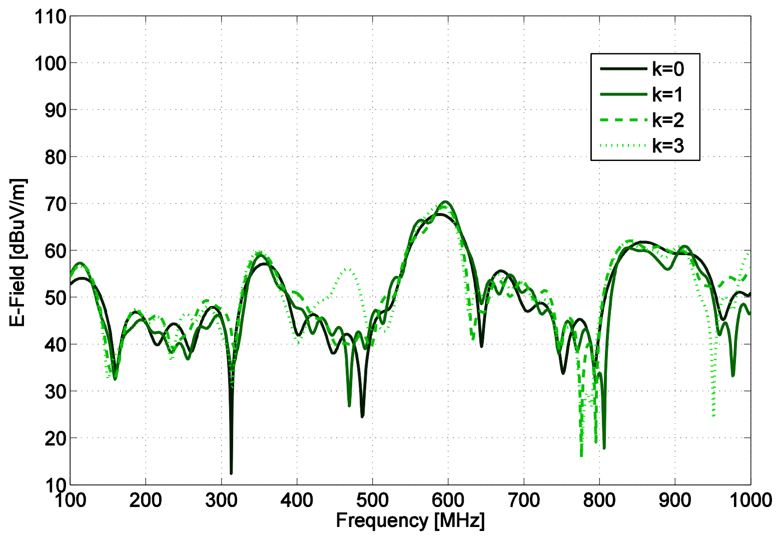


Figure 23. The effect of cable twist rate on observed radiation.

The effect of insulation permittivity and cable length on the radiation

The effect of insulation material relative permittivity (ε_r) of the power line cable on the radiation is simulated with permittivity values 3, 4, 5 and 6. These values present typical permittivity levels of plastic materials. From Figure 24 we can see that the permittivity of the insulation material changes the frequencies of peaks and notches in radiation levels. However, the average radiation levels remain generally unchanged.

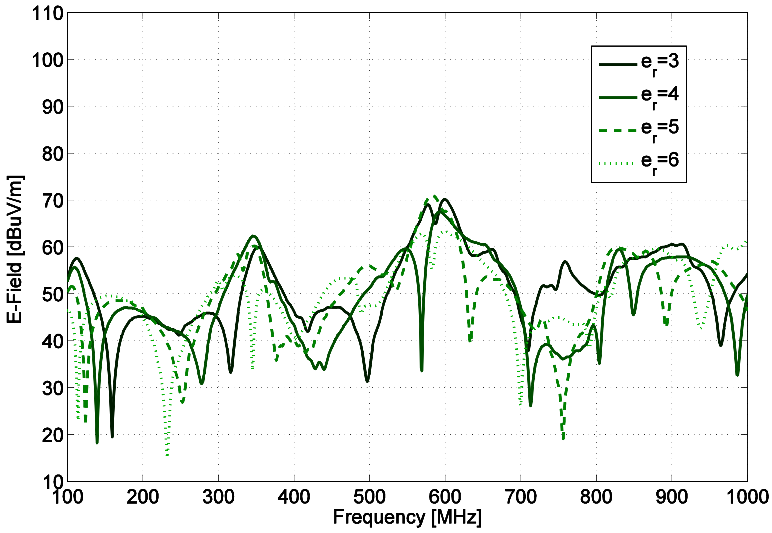


Figure 24. The effect of cable insulation material permittivity to the observed radiation.

Next, the effect of power line cable length on the radiation is simulated with 1.0 meters and 1.2 meters cable lengths. The simulation results can be seen in Figure 25. We can see that the frequencies of peaks and notches in the radiation levels change. However, again, generally the average radiation levels remain the same.

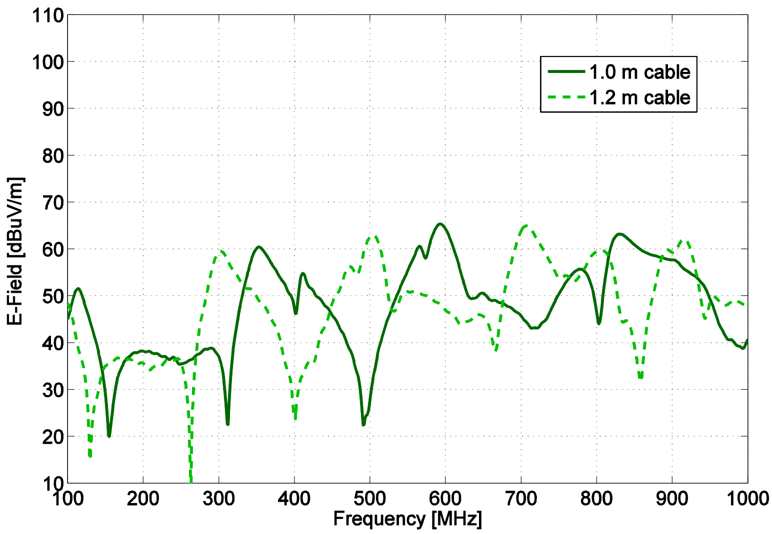


Figure 25. The effect of cable length to the observed radiation.

The effect of distance on the radiation

Due to near field effects, it is possible that the radiation level changes nonlinearly at distances closer than a certain threshold. The effect of distance on radiation level is simulated with a 1 m power line cable at distances 0.5, 1.0, 1.5, 2.0, 2.5 and 3.0 meters. From Figure 26 we can see that the radiation level changes linearly at distances further than 1.5 meters from the cable. At shorter distances we can see that the shape of the radiation level curve changes depending on the frequency.

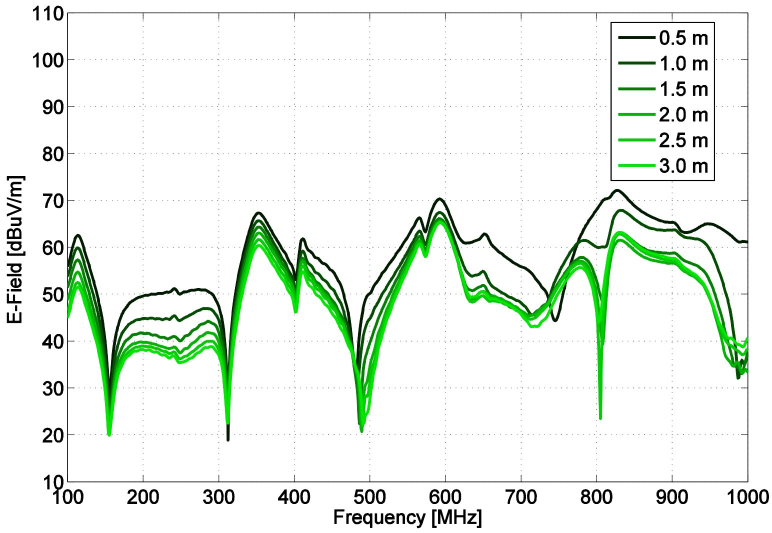


Figure 26. The effect of distance on the observed radiation.

Simulation results compared to EN 55022

The radiation of the power line cable is then simulated for cable lengths of 2 and 4 meters with BNC connectors at the each end. The results are compared to radiation limits in the EN 55022 standard at 3 meters distance. Figure 27 presents the simulation results. We can see that the radiation level has several peaks above the EN 55022 limit in the 100 MHz – 450 MHz and 700 MHz – 950 MHz frequency range. The radiation remains under the limit at the 460 MHz – 700 MHz frequencies.

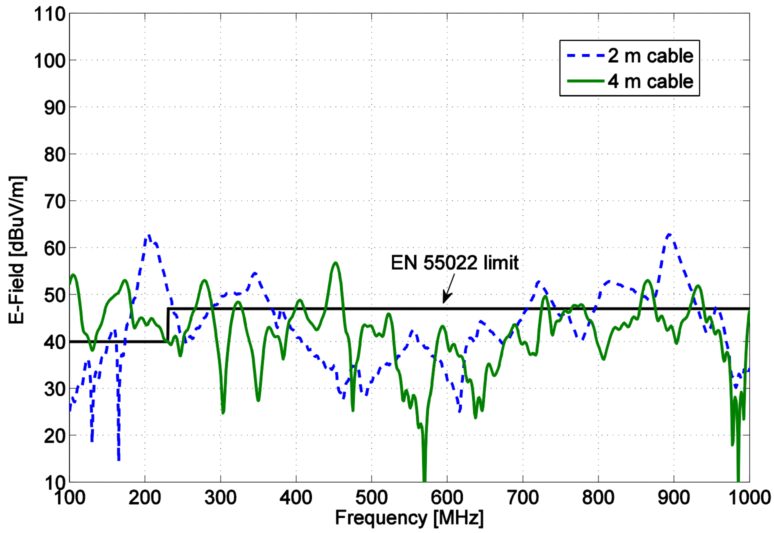
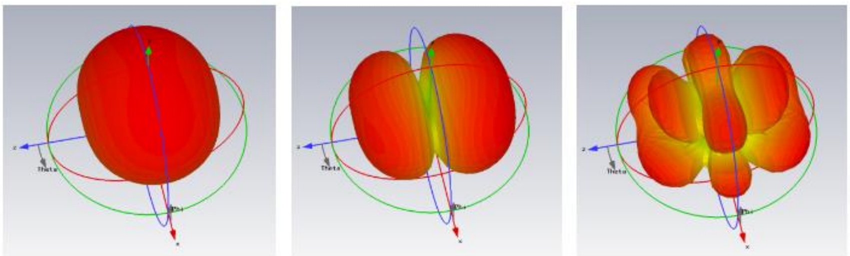


Figure 27. Simulated radiation of a 2 m and 4 m power line cable.

An analysis of the radiation patterns can be useful in determining the directions of the potentially highest interference levels. Figure 28 shows the free space radiation pattern of the 1 m power line cable at various frequencies. We can see that the pattern is omnidirectional at low frequencies. First null appears at 155 MHz frequency and this represents the half wavelength standing wave. A multiple of nulls and lobes appear as the wavelength decreases even further at higher frequencies.



(a) (b) (c)

Figure 28. 3D radiation pattern of a 1 m power line cable at (a) 112 MHz, (b) 155 MHz and (c) 351 MHz.

4.3.3. Results for plug and socket

The radiation caused by a plug and socket model seen in Figure 16 is simulated. Figure 29 presents the results on the front axis (directly towards the plug) and on the side axis (vertically above the socket). We can see that the electric field strength is up to 20 dB under the limit in the 100 MHz – 800 MHz frequency range. A linear rise in the radiation can be seen on frequencies above 650 MHz at the front axis of the plug and socket. The radiation level exceeds the limit above 900 MHz frequencies.

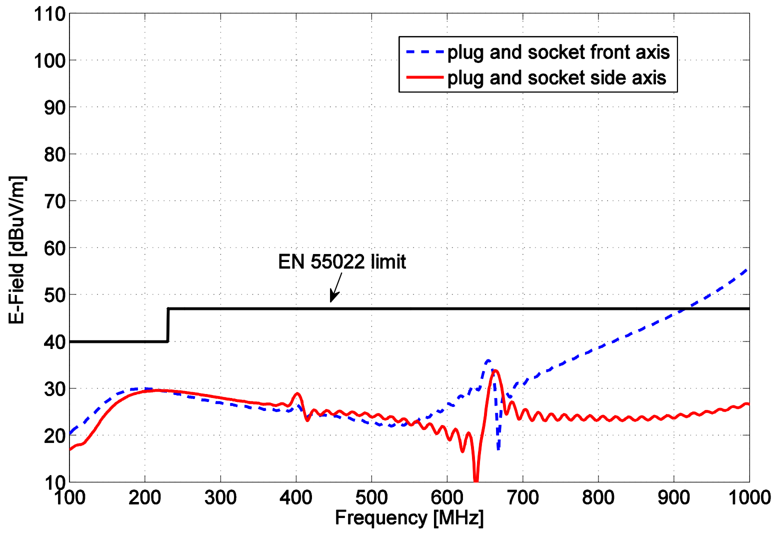


Figure 29. Simulated radiation of a plug and socket at 3 m distance.

4.3.4. Results for power line network

To combine the effects of plug and socket together with the cable, we can obtain results of simple power line network. The electric field strength caused by the 2 m and 4 m power line network (i.e. with plugs and sockets) can be seen in Figure 30. We can see that the radiation peaks are 13 dB over the limit in the 650 MHz – 1 GHz frequency range. Below the 650 MHz the average radiation level is approximately the same between the power line cable (i.e. without plugs and sockets) and power line network.

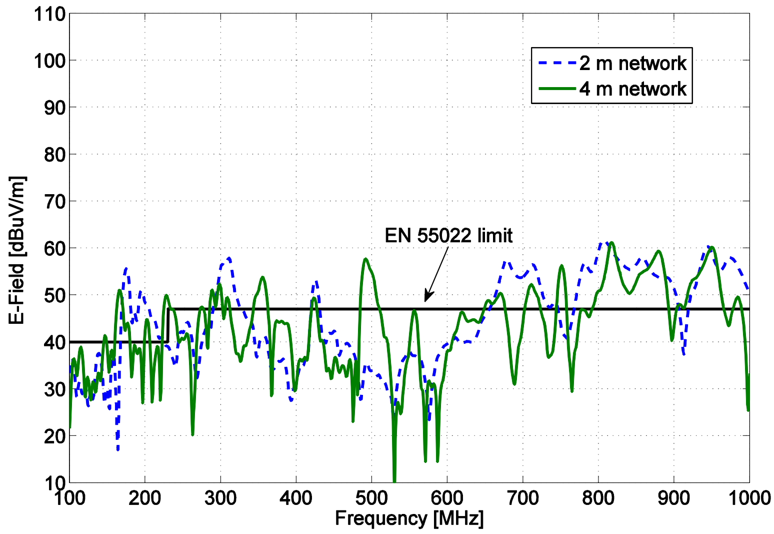


Figure 30. Simulated radiation of a 2 m and 4 m power line network.

5 RADIATED INTERFERENCE MEASUREMENTS

The radiated interference measurements of a segment of power line grid are presented in this chapter. The measurements are performed in a semi-anechoic EMC chamber at the University of Oulu.

5.1. Measurement conditions

The measurement equipment consists of a signal generator, a pair of couplers, a measurement antenna and an EMI receiver. The equipment is controlled through GIBP-connection with laptop PC. In the following, more detail is given about the measurement equipment, procedure and the test site.

5.1.1. Measurement equipment

Agilent E4426B [30] signal generator was connected to a coupler with a coaxial cable. The coupled feeds the signal differentially in the segment of a power line network arranged inside the EMC chamber. The network consists of plugs, sockets and power line cable. Detailed description of the coupler is given in [4]. An identical coupler was connected at the other end of a power line network with a 50 ohm load. Chase CBL6112 Bilog-antenna [31] was used to capture the electric field. Rohde&Schwarz ESCS30 EMI test receiver [32] was used to record the signal from the antenna with a 120 kHz measurement bandwidth. The antenna factor of the measurement antenna was programmed in to the EMI receiver. The antenna factor can be seen in Appendix 1. The attenuation caused by the coaxial cables was measured with a network analyzer. The attenuation effect was deducted from the measurement results. A flow diagram of the measurement system can be seen in Figure 31.

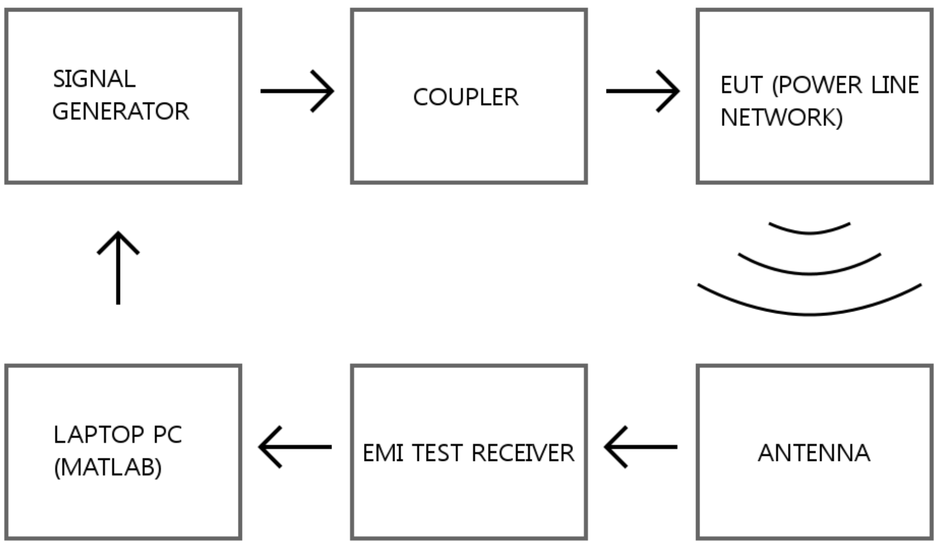


Figure 31. Flow diagram of the measurement equipment.

The signal generator and the EMI test receiver were controlled through a GPIB-connection with a laptop PC. A MATLAB script shown in Appendix 2 was used to set up the measurement and save the results. The signal generator frequency was swept in the 100 MHz – 1000 MHz frequency range with 500 kHz intervals. The input signal level was set according to Equation (1). The measurements parameters are presented in Table 8. A picture of the laptop PC, signal generator and EMI test receiver can be seen in Figure 32

Table 8. Measurement parameters

Parameter	**Value**
Frequency range	100 MHz – 1000 MHz
Frequency interval	500 kHz
Detector bandwidth	120 kHz
Detector type	peak
Signal power spectral density	- 80 dBm/Hz
Signal type	unmodulated carrier wave (CW)
Number of measurement points	1801

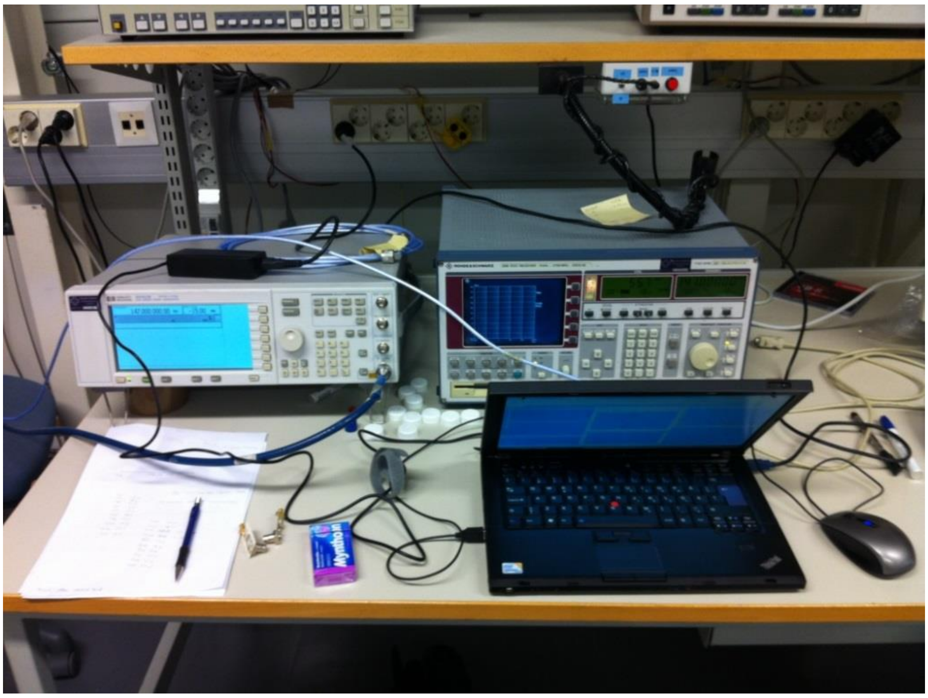


Figure 32. Signal generator, EMI receiver and laptop PC with GBIP-connection.

The radiation limits in the EN55022 standard are given for quasi-peak detection mode. For a highly repeating signal such as the carrier wave signals injected from the signal generator the results are effectively the same in the peak and quasi-peak detection mode. The peak mode saves considerable amount of time as the measurements in quasi-peak detection can take up to several hours of time for a single sweep. Thus a peak detection mode was chosen for the measurements.

5.1.2. Measurement test site

The EMC chamber length is 11.5 meters, the width is 6.5 meters and height is 6.5 meters. The chamber has a 76.7 m^2 conducting ground floor and anechoic wall materials in full compliance to EMC measurement standards. A segment of a power line network was constructed horizontally in the EMC chamber as can be seen in Figure 33. The power line cable and the sockets are attached to a structure that places the system at a 1 m height from the ground floor. The structure is constructed with non-reflecting wood and plastic materials. Chase CBL6112 Bilog-antenna [31] captures the electric field at a 3 meters distance. The antenna was placed 1 meter above the ground plane.

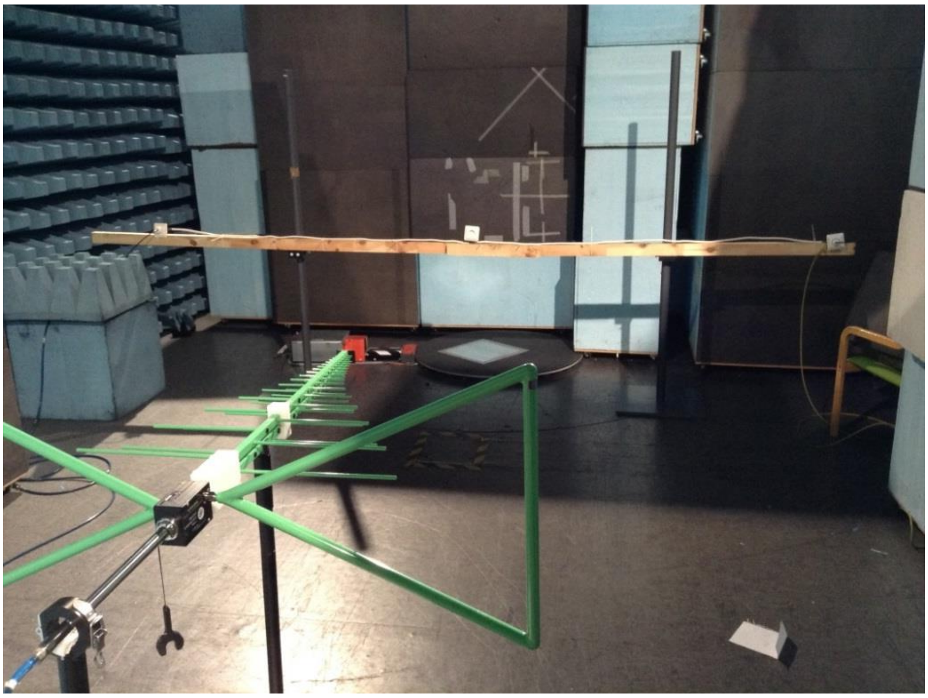


Figure 33. Measurement test site.

5.2. Measurement results

First, measurements are performed for the power line cable. The measurement results for a 2 meter and 4 meter power line network, i.e. with plug and socket at the each end, are presented next. Finally, a third socket was added to the center of the 4 meter network and the results are compared to the two socket situation. The measurement results are compared to the EN55022 limits. The highest radiation levels were found to be in the horizontal antenna position.

5.2.1. Power line cable

A 1 meter power line cable is measured with and without the outer PVC insulation material that is holding the individual wires together. The twisting of the individual wires is also removed when removing the outer PVC. The signal power level during the measurement was set to -75 dBm/Hz equivalent PSD. From Figure 34 we can see a 20 dB dip in radiation at 240 MHz without the outer PVC (i.e. with straight wires).

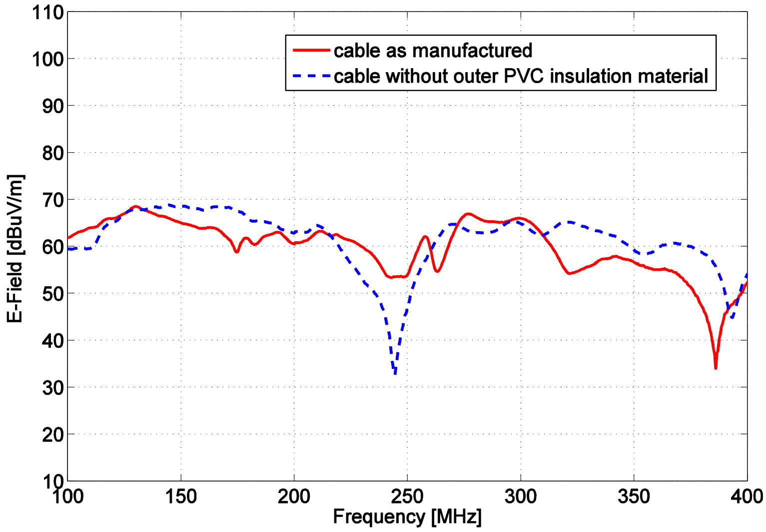


Figure 34. Measured radiation of a 1 m power line cable.

5.2.2. 2 meter power line network

Figure 35 presents the measured electric field strength caused by a 2 meter power line network from a 3 meters distance. We can see that the peak levels of radiation are approximately 13 dB over the EN55022 limit in the 300 MHz – 450 MHz frequency range. A single peak can be seen 18 dB over the limit at the 140 MHz frequency.

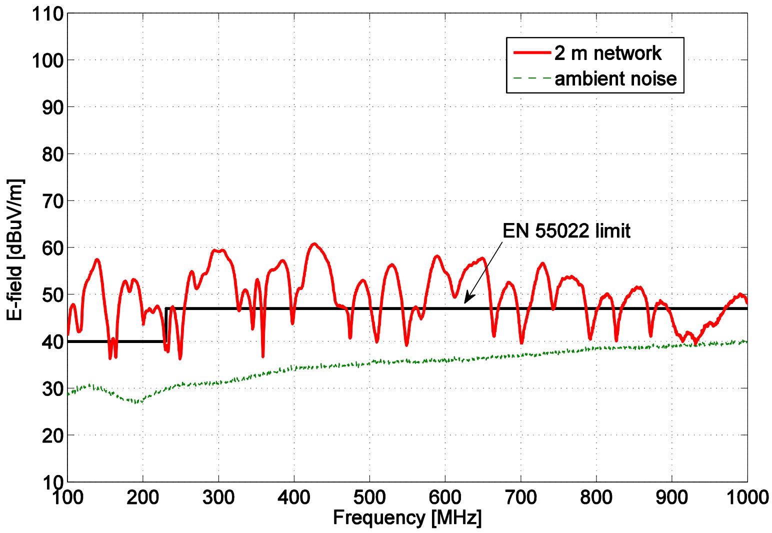


Figure 35. Measured radiation of a 2 m power line network.

5.2.3. 4 meter power line network

Electric field strength caused by the 4 meter power line network can be seen in Figure 36. We can see that compared to the 2 meter network the radiation level is reduced in the 100 MHz – 700 MHz frequency band. The peak levels are 10 dB above the EN55022 limit. The radiation level remains mostly under the EN55022 limit in the 450 MHz – 700 MHz frequency band.

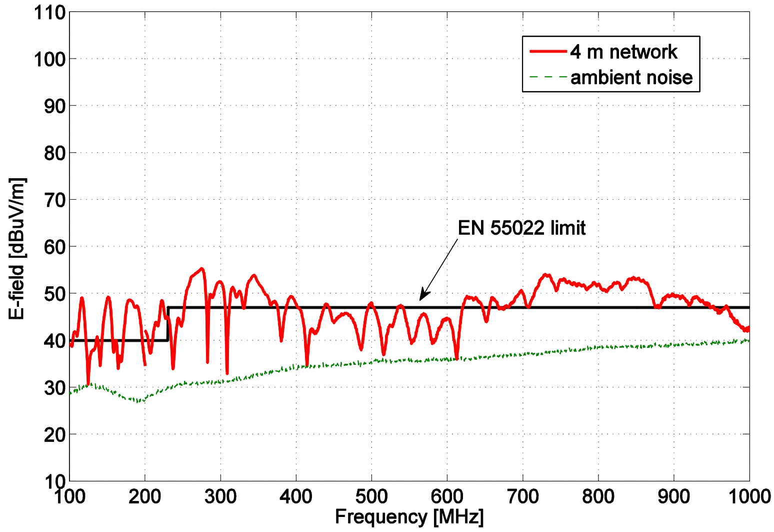


Figure 36. Measured radiation of a 4 m power line network.

5.2.4. 4 meter power line network with three sockets

To study the effect of an additional socket to the overall radiation level, a third socket is added to the center of the 4 m network. Figure 37 presents the comparison of the radiation levels with and without the center socket. We can see that the center socket increases the radiation levels in the 260 MHz – 420 MHz frequency band. The peak levels are 13 dB above the EN 55022 limit.

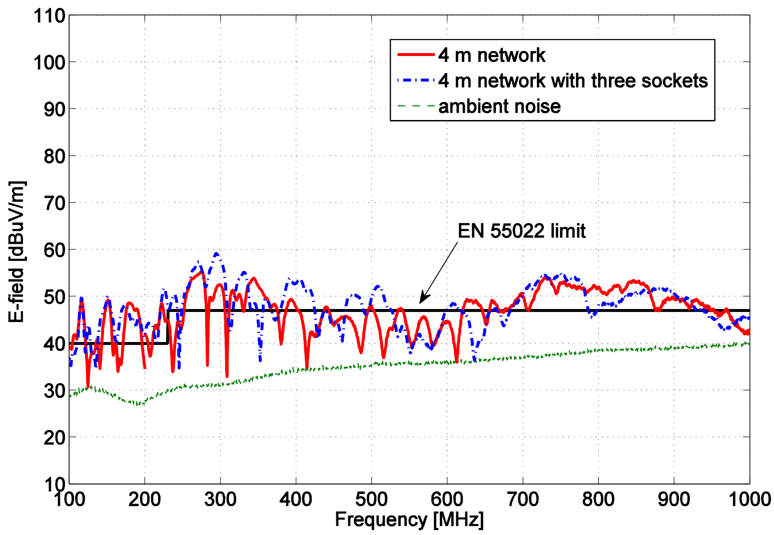


Figure 37. Measured radiation of a 4 m power line network with center socket.

6 DISCUSSION

The simulation and measurement results correlate well on the amount of peak radiation levels and roughly on the shape of the radiation-frequency curve. However, the exact frequencies of peaks (and dips) in radiation are different between the simulations and measurement. The possible reason for this is the perfectly symmetrical nature of the structures and materials in simulation model. In reality the materials are not perfectly uniform and the structures are not perfectly formed. The simulations however predict the overall radiation level accurately. It is important to have realistic simulation models in order to produce results that correlate accurately with reality.

The results show that the radiation is mainly caused by the power line cable in the 100 - 1000 MHz frequency range. The components of the power line network, i.e. plugs and sockets studied in this thesis, increase the peak levels of radiation by up to 10 dB on certain frequency ranges. The effect of other types of components, e.g. junction boxes, switches or connectors and loads connected to the power line network, was not studied in this thesis and remains as a further study.

The length of the power line cable or network, 2 m and 4 m studied here, affects the overall radiation level. The radiation is increased in the shorter 2 m length case, specifically in the 300 – 700 MHz frequency range.

The twist rate of the individual conductors in the power line cable or the permittivity of the insulation materials does not seem to affect the overall simulated radiation levels. However, the frequencies of individual peaks and dips are changed by these factors.

Measurements of radiation proceeded according to international EMC standards are needed for verification of the simulation results. However, the physical dimensions of the actual EMC chambers limit the size of the power line network that can be constructed inside the chamber. In-situ test sites and on-location measurement campaigns are needed in order measure the radiation of realistically sized power line networks that exist in-house of in-office buildings. It should be noted that the effect of measurement antenna height to the measured radiation was not studied in this thesis. The antenna was located on fixed height of 1 meter above the ground plane.

Typical in-house or in-office power line networks can have multiple kinds of topologies. The branches can have different lengths of cable and the cables can curve inside walls or corners. The network can have different types of loads connected to it and some of the loads can be impulsive or changing while other are more static. The materials and construction types of the buildings can also affect the amount of radiation measured in- or outside the building. Different types, i.e. cables with or without protective earth wire, and dimensions of individual conductors in different countries can also affect the radiation and because of that the levels and frequencies of radiation peaks (and dips) may differ from country to country.

The 3D radiation pattern of the power line network can also differ from frequency to frequency, i.e. the radiation levels on different frequencies depend on the location of the measurement point.

7 SUMMARY

In order to have sufficient understanding of the radiation of the power line network in the 100 – 1000 MHz frequency range more complex simulation models and measurement campaigns are required with different type of cables, components, loads, network topologies and locations. To best of our knowledge, no other published work exists in the time of writing this thesis that have analyzed the radiation of power line network on above 100 MHz frequencies with both measurements and simulations. This thesis can be seen as valuable information for future studies and measurement campaigns. It provides simulations and measurements of the leaked radiation levels in the 100 – 1000 MHz frequency range for the typical components of the in-house or in-office power line network.

The results indicate that the peak levels of radiated interference from a typical cabling in in-house or in-office power line networks reach their maximum on frequencies near 300 MHz and remain on a relatively same level on above. The peak levels are approximately 13 dB above the EN 55022 limit in the 230 MHz – 1000 MHz frequency range with an injected power spectral density of -80 dBm/Hz.

The majority of the radiation is caused by the power line cable itself. However, the components of the power line network, e.g. plugs and sockets, can add up to 10 dB of additional radiation on certain frequencies. The twist rate of the individual wires in the power line cable does not affect the average radiation level. As does not the permittivity of the insulation materials of the cable. Only the frequencies of the individual peaks and dips in the radiation are affected.

However, the overall structures of the used power lines dictate the radiation patterns as well as the amount of radiation. Depending on the geometry of the elements of the power grids as well as the structure of the connections, the radiation can easily vary 20 dB for frequencies above 100 MHz. The length of the cables together with the structure can cause the radiation frequencies deviate both in direction and in strength. The accuracy of used models is critical when determining the interference levels by simulations. In order to specify the allowed transmission signal powers, we need further measurement campaigns and analysis. Average interference values throughout the spectrum can be obtained easily but if we want more efficient spectrum utilization, we need to have more intelligence spectrum sensing methods that adapt to the prevailing environment. This remains as a further study.

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9 APPENDICES

Appendix 1 Chase CBL6112 Antenna Factor

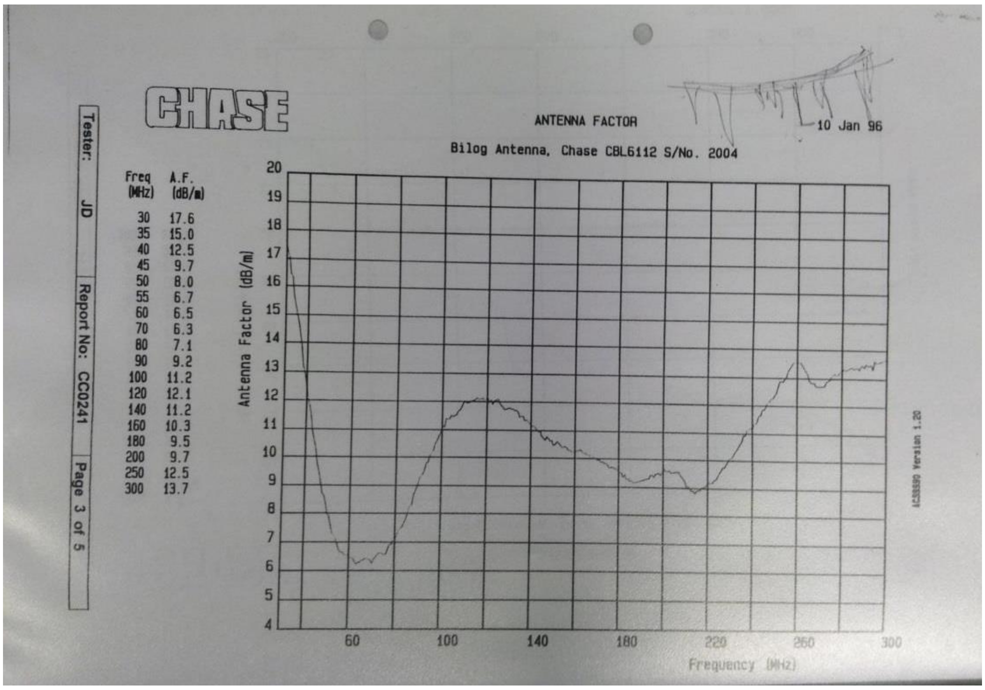

Figure 38. Antenna factor in the 30 – 300 MHz frequency band.

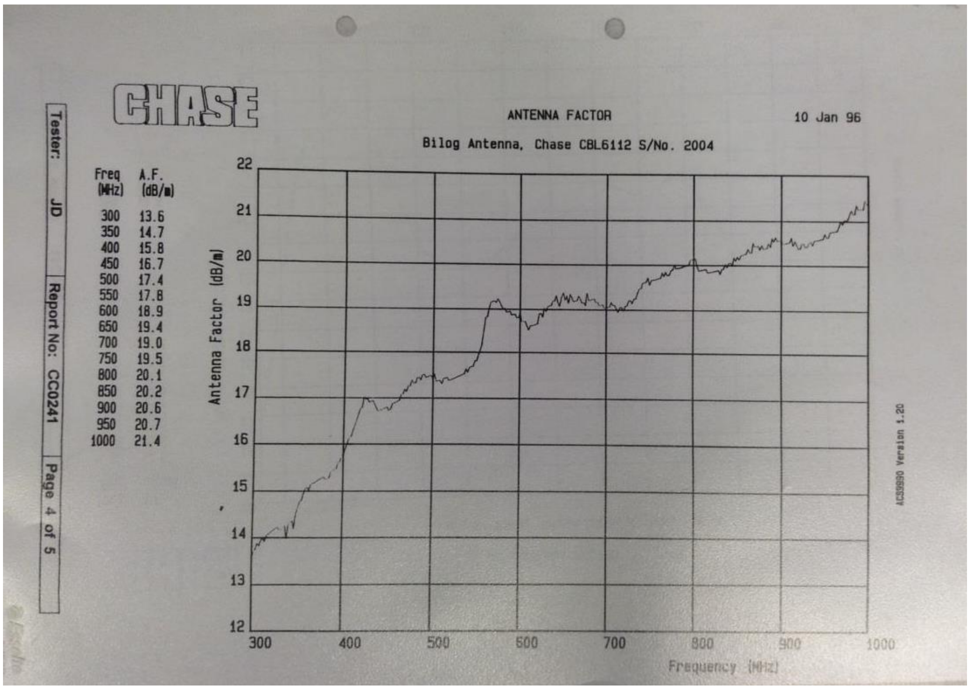

Figure 39. Antenna factor in the 300 – 1000 MHz frequency band.

Appendix 2 MATLAB Code for GBIP Controller

```
values=0;
%obj1 = gpib('NI', 0, 18); %id of R&S analyzer, check that it is correct in your
case.
obj1 = instrfind('Type', 'gpib', 'BoardIndex', 0, 'PrimaryAddress', 18, 'Tag', '');

if isempty(obj1)
    obj1 = gpib('NI', 0, 18);
else
    fclose(obj1);
    obj1 = obj1(1);
end
obj2 = instrfind('Type', 'gpib', 'BoardIndex', 0, 'PrimaryAddress', 26, 'Tag', '');
if isempty(obj2)
    obj2 = gpib('NI', 0, 26);
else
    fclose(obj2);
    obj2 = obj2(1);
end
%obj2 = gpib('NI', 0, 26); %id of used Agilent generator, check that it is correct
in your case.

fopen(obj1);
fopen(obj2);
tic
for k=-25:5:-15

c=':POW:LEV';
poweri=int2str(k);
d='dBm';
temp_power=strcat([c , ' ', poweri,' ', d]);
fwrite(obj2,temp_power);

level_all=[];

for i=30000000:500000:200000000
%i=31000000
a='FREQUENCY';
b='FREQ:FIX';
f=int2str(i);
temp=strcat([a , ' ', f]);
temp2=strcat([b , ' ', f]);
fwrite(obj2,temp2);


for j=1:10
fwrite(obj1,temp);

fwrite(obj1, '*TRIG;*WAI');
%fwrite(obj1, 'LEVEL:LASTVALUE?');
fwrite(obj1, 'LEVEL?');
data1=scanstr(obj1);
temp3=cell2mat(data1);
temp4=strsplit(temp3);
temp5=cell2mat(temp4(1,2));
level(j)=str2num(temp5);
end
level_all=[level_all;level];

%values=[values data1];

end
nimi=strcat(['level_' , poweri]);
save(nimi,'level_all');

end
toc
fclose(obj1);
fclose(obj2);
```